Geo

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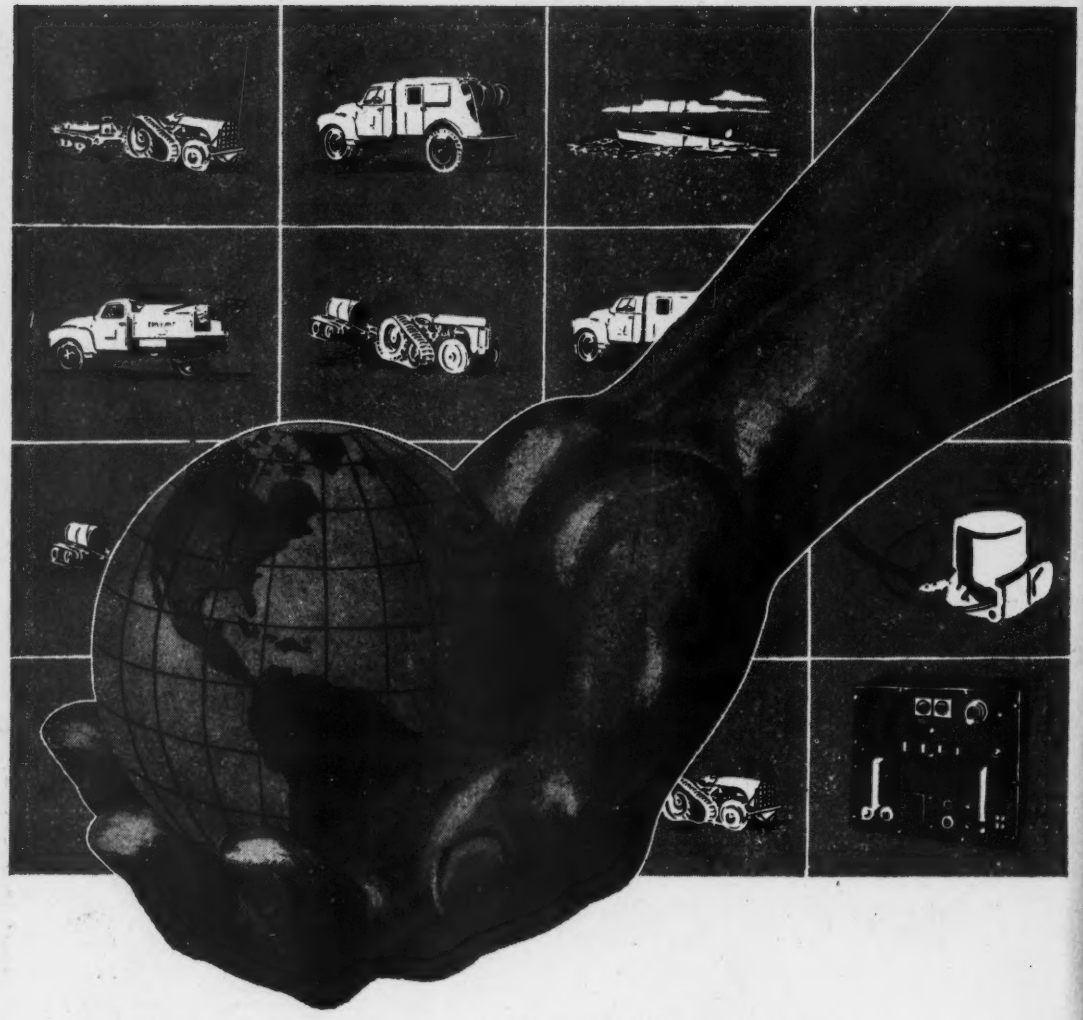

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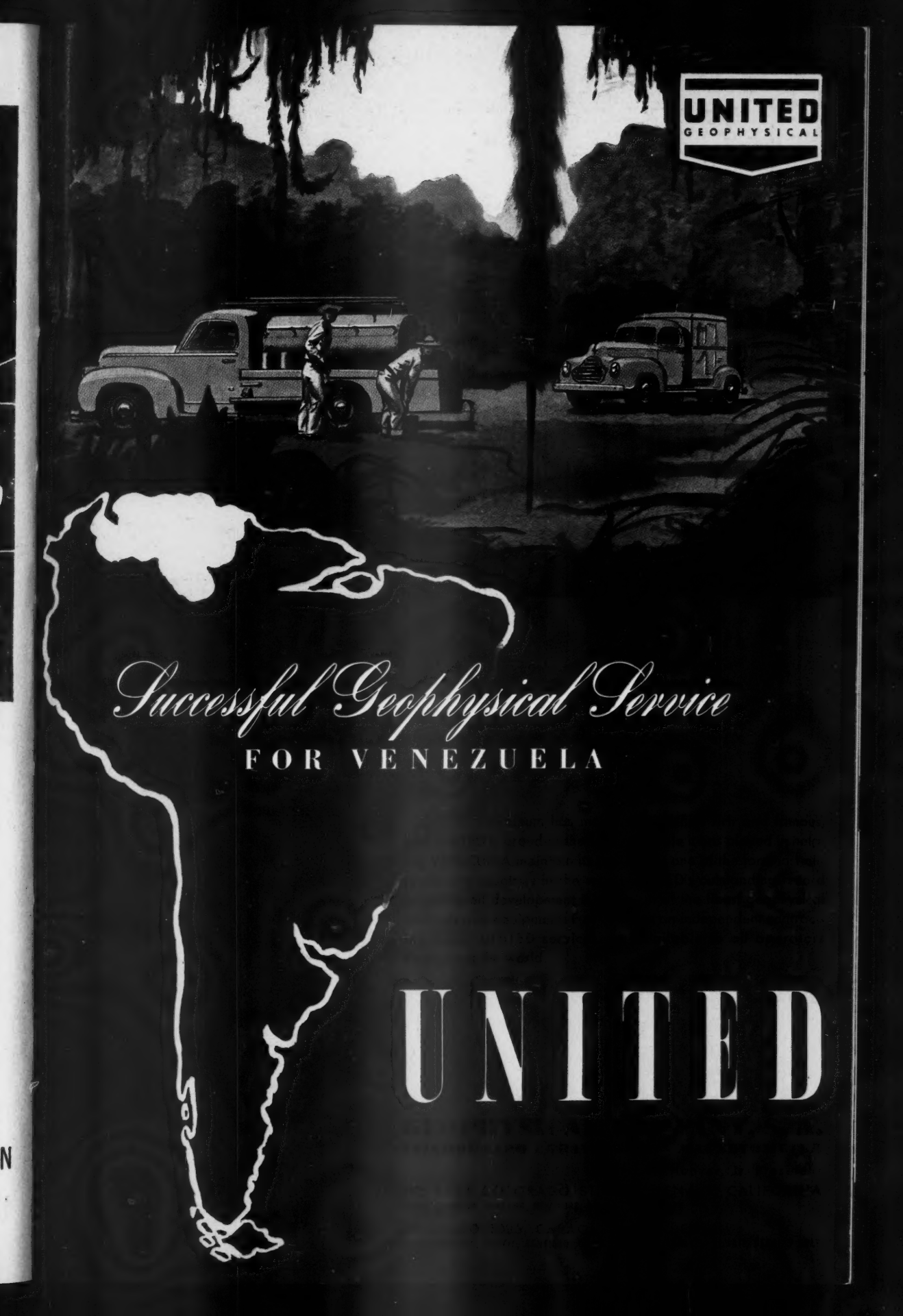
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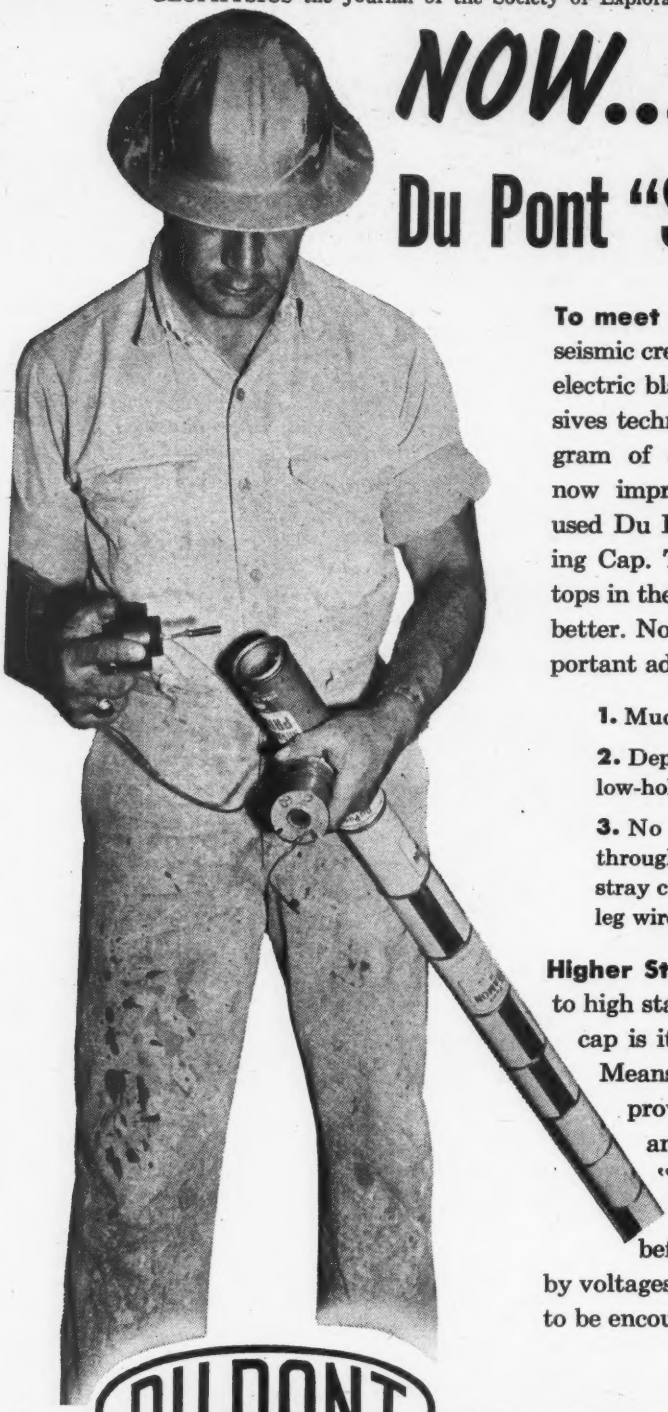

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RULES OF THE CONTEST

1. Entries, to qualify, must be received at the business office of the Society of Exploration Geophysicists, Box 7248, Tulsa 18, Oklahoma, on or before March 1, 1952. Only active, associate or student members in good standing of the Society of Exploration Geophysicists shall be eligible to enter. Current officers and members of the Standing Committee on Honors and Awards are not eligible to receive prizes.

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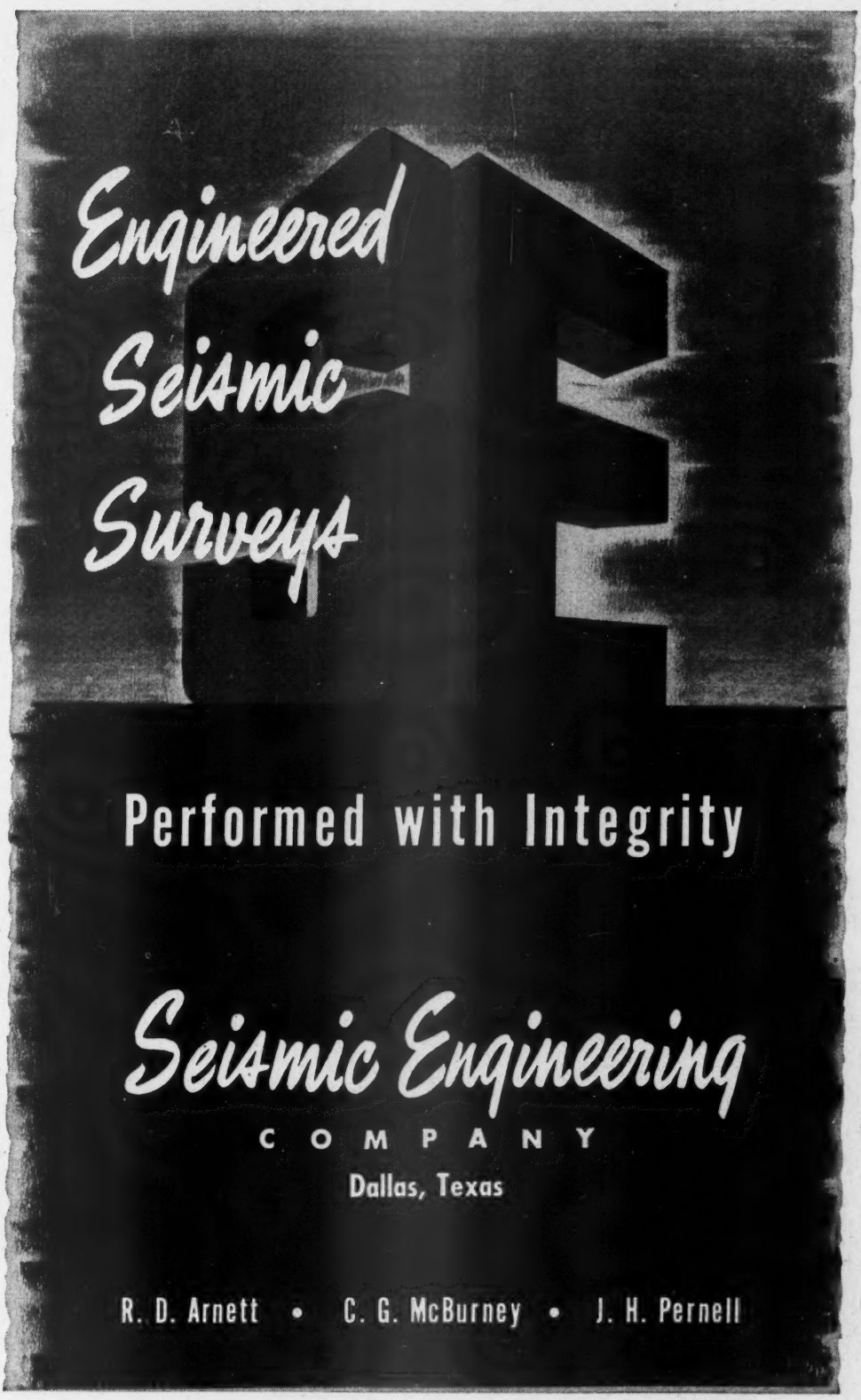
3. The Standing Committee on Honors and Awards shall be the sole judges. All entries shall become the property of the Society of Exploration Geophysicists and cannot be returned to contestants. In the event no design is chosen, the Society reserves the right to extend the contest.

4. Announcement of the results will be made at the 1952 annual meeting.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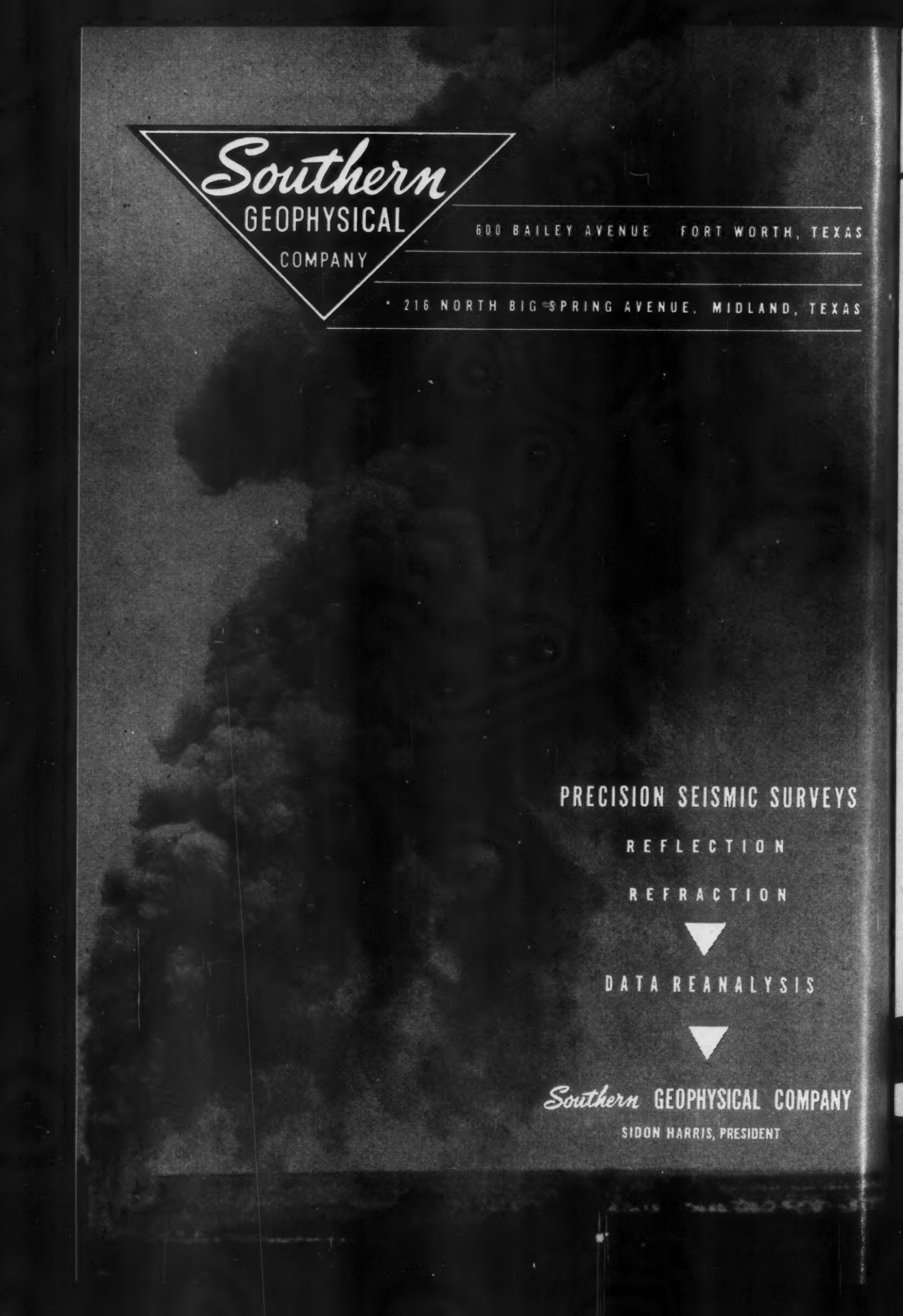
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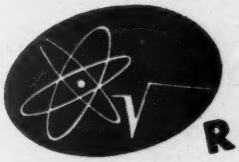

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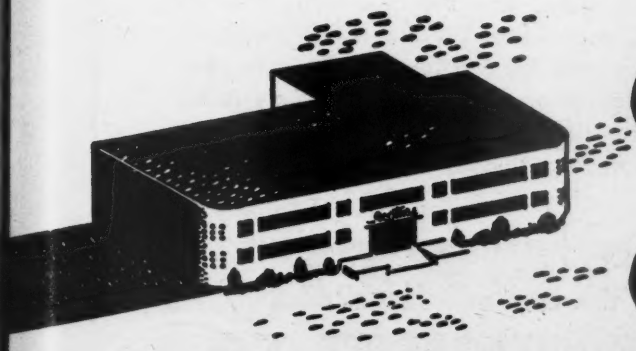

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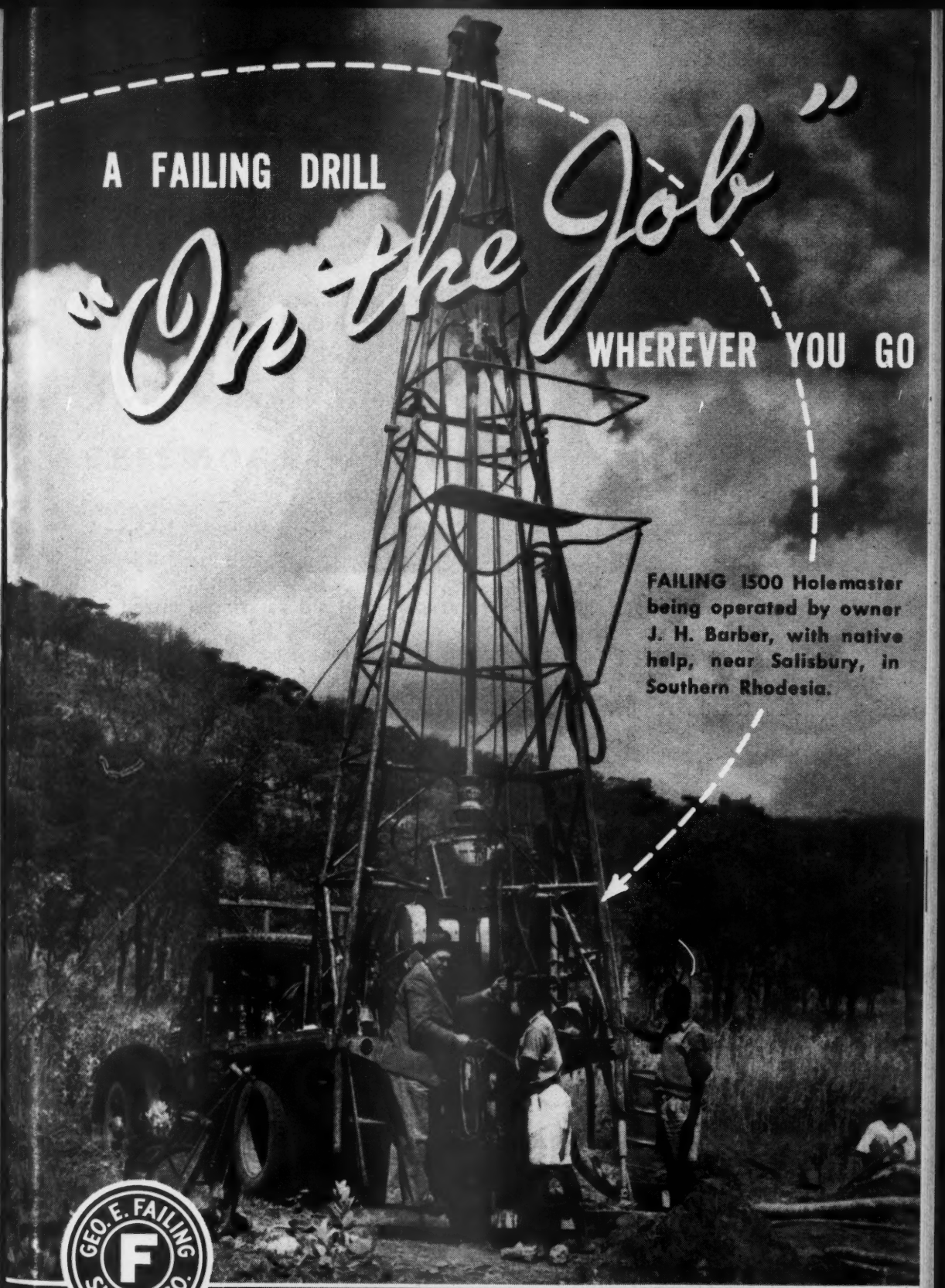
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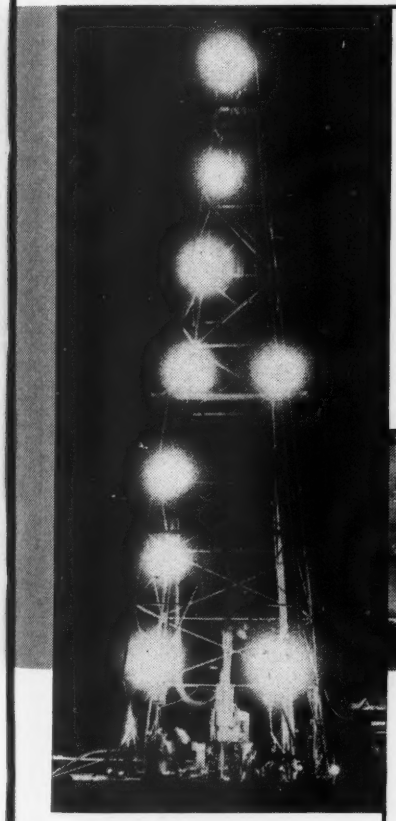

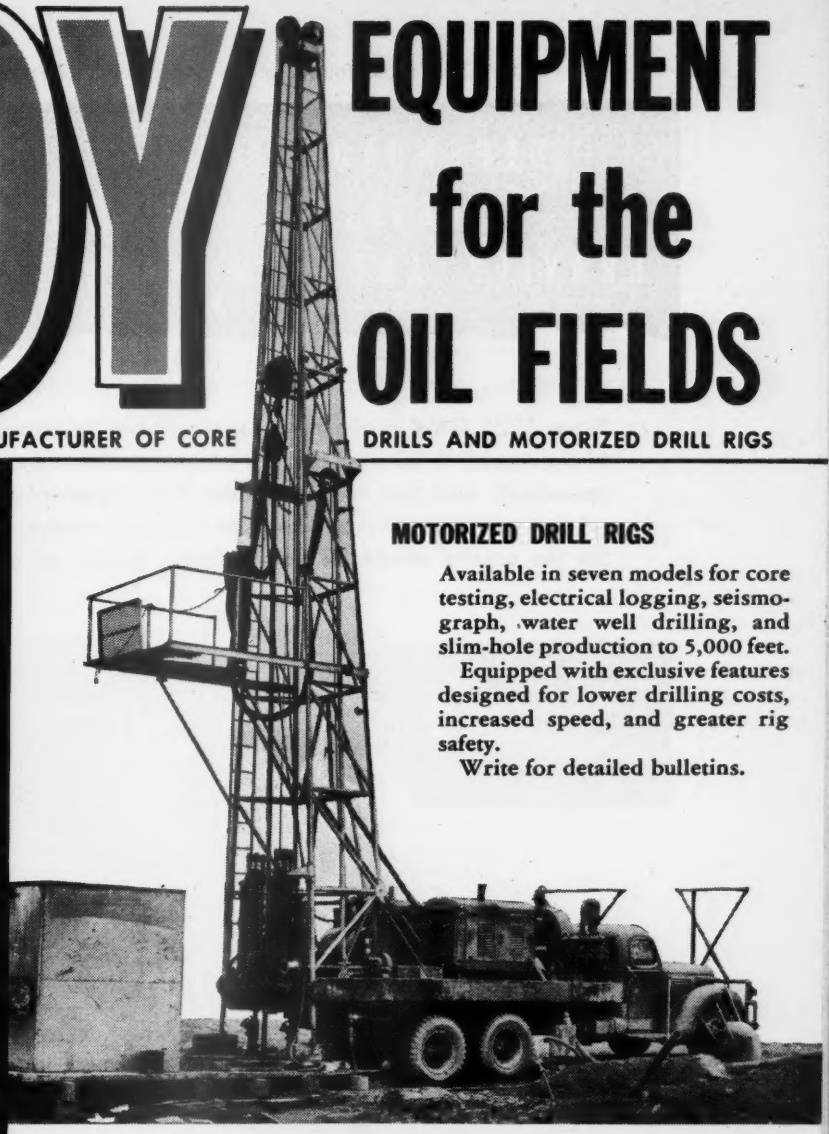

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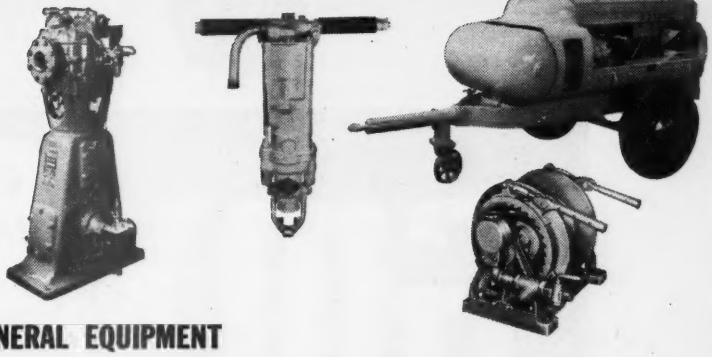

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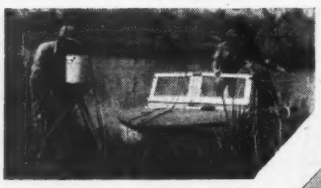

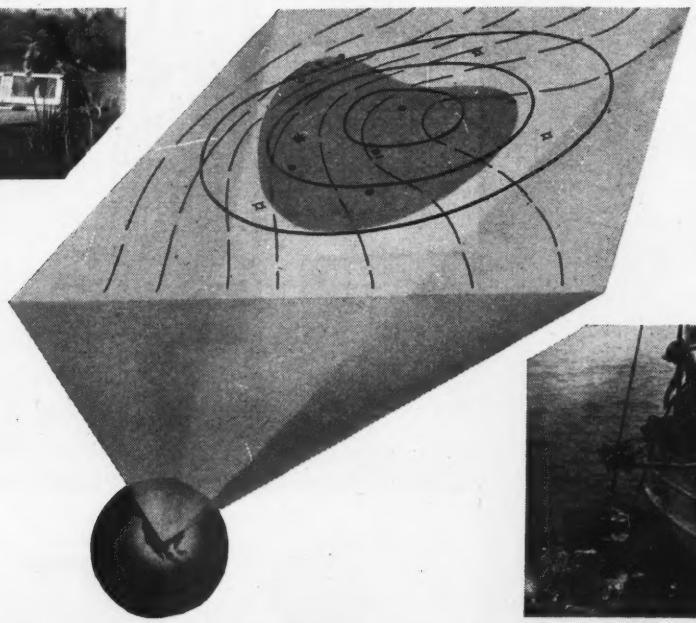

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GEOPHYSICS

A Journal of General and Applied Geophysics

ELASTIC WAVE VELOCITIES IN ROCKS AT HIGH PRESSURES AND TEMPERATURES*

D. S. HUGHES† AND J. H. CROSS†

ABSTRACT

The variation in dilatational and rotational velocities in rock samples with pressure and temperature has been studied. The measurements were taken at pressures from 1 bar (atmospheric) to 5,000 bars, and temperatures of 25°C. to 200°C. for all samples and up to 300°C. for two samples. We can thus reach a pressure equivalent to some 18 km or 60,000 feet of burial but our highest available temperature probably at most corresponds to no more than 8–9 km.

The measured rotational velocities check very well with independent measurements. Laboratory measurements of the dilatational velocity are not available for comparison. From the measured dilatational and rotational velocities, the elastic moduli and Poisson's ratio may be computed. Values of Poisson's ratio are tabulated for all samples. In general, highly quartzitic rocks have low values 0.13–0.20 whereas the majority of rocks have values in the range 0.26–0.33.

The effect of interstitial water has been investigated in one sandstone and one limestone. The sandstone shows an increase in velocity at low pressure and a decrease at high pressure whereas the limestone shows the opposite effect.

INTRODUCTION

A method of measuring both the dilatational and rotational wave velocities that is applicable to small laboratory samples has been developed and has been in use for some time (Hughes, Pondrom, and Mims, 1948). It is particularly applicable to rocks and to measurements in pressure chambers (Hughes and Jones, 1950) since the velocities are obtained from measurements of the transmission time of pulses through the sample. It is thus possible to measure high loss materials to which resonance methods would either be inapplicable or inaccurate. With a few minor exceptions to be discussed later, the boundary conditions of the sample are unimportant.

APPARATUS

A block diagram of the pressure apparatus is presented in Figure 1. It consists of two systems, including a low pressure system consisting of a hand pump and

* This work was supported by the Office of Naval Research under Contract N6onr-266, Task Order VIII, and by research grants from the Shell Oil Company and the Humble Oil and Refining Company. Manuscript received by the editor May 21, 1951.

† Department of Physics, the University of Texas, Austin, Texas.

dead weight gauge that are used over the range 1.0–1,000 bars. At the latter pressure the high pressure valve is closed and an auxiliary pumping system is used to raise the piston in the pressure intensifier. The volume displacement of the intensifier is sufficient to raise the pressure in the sample and gauge cylinders to about 6,000 bars. The sample cylinder is 1.40 inches inside diameter and 7.0 inches inside height. Two insulated electrical leads are brought through the chamber head. An electric furnace can be placed around the sample cylinder and the temperature raised to 300°C.

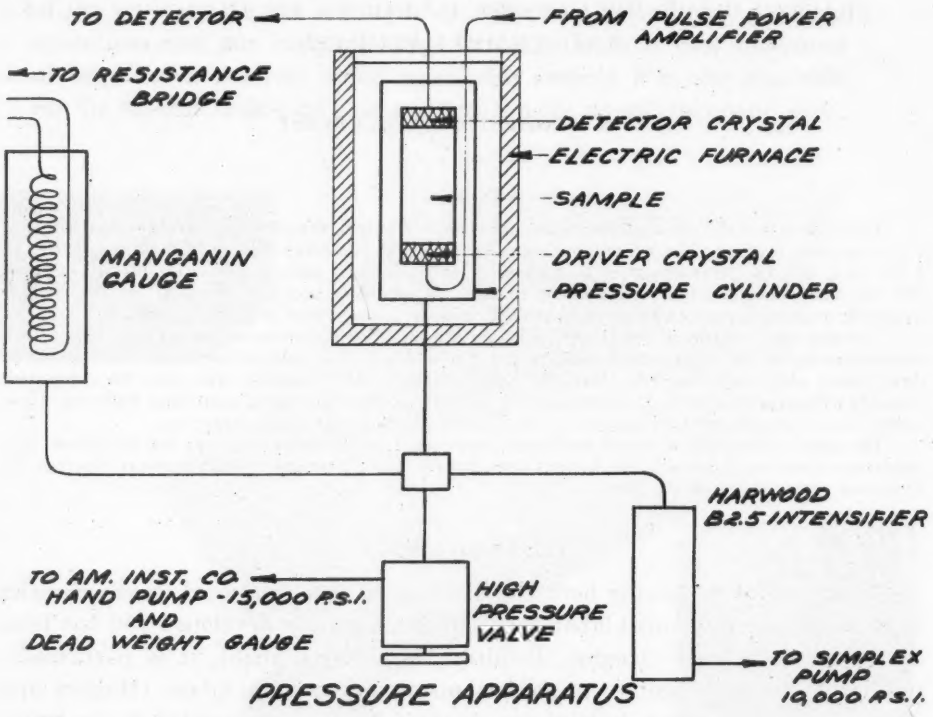

FIG. 1. Block Diagram Pressure Apparatus.

A block diagram of the electronic equipment is presented in Figure 2. This has been modified somewhat from that described in the references. The essential method is the same but the number of components has been reduced by substantially rebuilding the TS/100 AP range oscilloscope into a double oscilloscope capable of presenting A, J, and R displays. The oscilloscope delivers a trigger pulse at intervals of 2 to 3 milliseconds. These pulses are delayed about 5.0 μ sec by the delay line, amplified by the pulse amplifier, and impressed on the driving crystal. The signal from the receiving crystal is amplified and returned to the oscilloscope. The time between the trigger pulse and the received pulses can be read to about 0.02 μ sec on the oscilloscope.

The samples are cylindrical cores about 1.0 inch in diameter by 1.5–3.25 inches long. The longer cores are preferred but good values of V_D can be obtained with short cores. These are cut from well cores or block samples with a diamond drill. The cores are usually jacketed by placing them in a close fitting copper tube, with wall 0.012 inch, and cutting the tube off even with the rock. The ends of the core are ground to provide a good surface and copper caps 0.010 inch thickness placed over the ends. The caps are spun down on the tube and overlap about 0.3–0.4 inch. The seal between the caps and the tube has been made in several different ways. If the core is to be measured to 300°C. a special

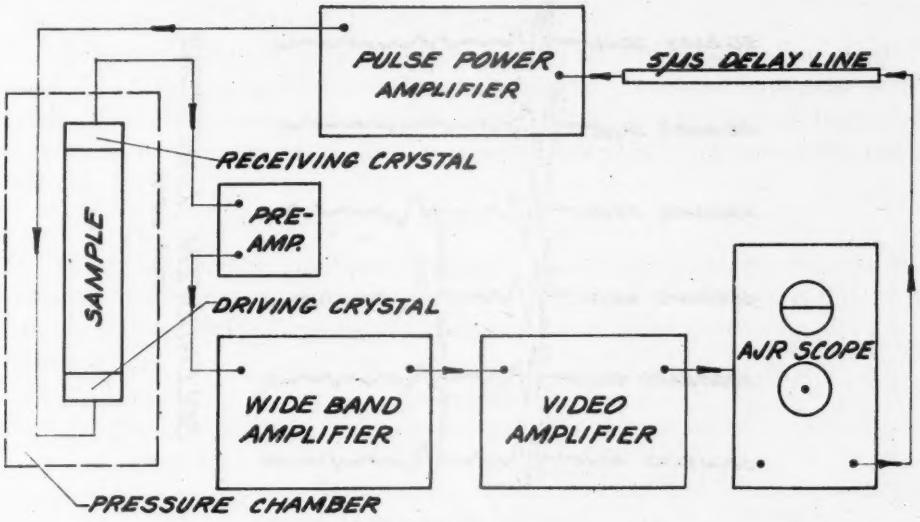

FIG. 2. Block Diagram Electronic Apparatus.

lead-silver solder is used. This has the severe disadvantage that the core must be dry in order to make the seal. Dr. Birch has used rubber tubes for jackets and the authors have been very successful with neoprene tubing, but these cannot be heated much above 200°C. in the pressure chamber. Neoprene tubing has been used, however, for all cores with included water. Dr. D. H. Reno of the Stanolind Oil Company has suggested the use of Teflon tubing. This material will stand the temperature and pressure but is difficult to seal at low pressures.

THEORY

The appearance of the transmitted pulse is shown in Figure 3. This record was taken with a sample of Solenhofen limestone in the pressure chamber. The

first arrival is the direct dilatational wave through the sample. The length of this sample is 8.252 cm. An arrival time of 13.56 μ sec gives 6,086 meters/sec for V_D. At the higher pressures it will be noted that following the first arrival

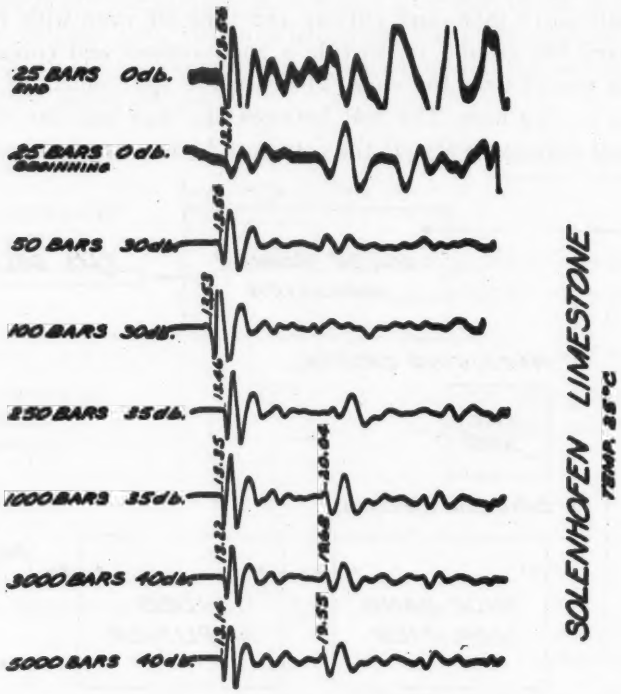

FIG. 3. Pulse Arrivals Solenhofen Limestone.

there are others at intervals of about 6.60 μ sec. These later pulses have been shown to arise from the incident dilatational pulse being transformed at the boundary and crossing the rod as a rotational wave and being transformed into a dilatational wave at the opposite boundary (Mason and McSkinin, 1947).

In general we may write (Hughes, Pondrom, and Mims, 1948),

$$t_{mn} = (2n + 1)L/V_D + mD(V_D^2 - V_R^2)^{1/2}/V_D V_R \qquad (4.a)$$

as the times of arrival of the pulses from a single excitation of the driving crystal. Where L = length of sample

D = diameter

V_D = dilatational velocity

πV_R = rotational velocity

m and n are integers subject to the condition

$$(2n + 1)L \geqq mD \tan \theta \qquad (4.b)$$

where

$$\theta = \sin^{-1} V_R/V_D. \tag{4.c}$$

There is no well defined limit to the values that m and n may take subject to the above condition. With metal rods of good acoustic properties, values of n as high as 8 or 9 and values of m of about 7 have been observed. With rocks, Figure 3 shows about the best results. The first arrival corresponds to $n=0$, $m=0$. The second arrival corresponds to $n=0$, $m=1$. The arrival with $n=0$, $m=2$ is visible but not readable even at the highest pressures. At the very end of the traces, the arrival $n=1$, $m=0$ is visible. This, of course, is the pulse that has travelled the length of the rod three times.

Evidently if the arrival times of the 0,0 and 0,1 pulses can be read, both V_D and V_R can be computed. Since these velocities are computed from pulse arrival time, they are actually the velocity corresponding to the band of frequencies necessary to form the break. In the present work this is approximately 1.0–5.0 mc.

RESULTS

In spite of the high equivalent frequency, our velocities check very well with other measurements at lower frequencies, with one possible exception to be discussed later. Table I presents a comparison of our measurements of V_R with Birch (1942).

TABLE I

Pressure	V_R (meters/sec) Solenhofen Limestone	
(bars)	Birch	Authors
1	2,750	2,854
500	2,910	3,008
4,000	3,080	3,066

In addition to the Solenhofen limestone, samples of the Quincy granite, Twin Sisters dunite, Cheshire quartzite, and Danby marble have been measured by Dr. Birch and ourselves. Our value on the Quincy granite is about 10 percent low and apparently must be ascribed to a leak. Dr. Birch's values for the other rocks have not as yet been published. Our value for the quartzite checks well with other quartzites studied and the one value for the dunite is close to that of Birch but this rock shows some anisotropy.*

Dr. Birch's measurements were made at frequencies of several kilocycles by a resonance method. Because of the damping under pressure by the transmitting fluid, V_D cannot be measured by this method. We have not been able to get a direct check in our measurements of V_D in rocks (Hughes and Jones 1950).

* Personal communication.

The values measured so far have been very reasonable. A better check is probably the values of Poisson's ratio computed from V_D and V_R. Our computed values are regarded as very reasonable and since a small change in the velocities will make a large change in this quantity, it constitutes an excellent check. Table XI shows computed values for Poisson's ratio for several rocks under different conditions. It will be noted that quartzitic rocks tend to show a low value in general.

Table II shows the V_D and V_R for dunite from Twin Sisters Mountain in Washington. This dunite, from thin section study, is 90 percent olivine and 10 percent augite. The olivine crystals form an interlocking mosaic with a scat-

TABLE II

Core #123, Sample 28
Density 3.160

Description: Dunite
Origin: Twin Sisters Mtn., Washington

T—°C.	24.5		100		200		300		24	
P (bars)	V_D	V_R	V_D	V_R	V_D	V_R	V_D	V_R	V_D	V_R
70	8,603	4,185	8,367	4,224					8,725	4,390
138	8,694	4,244	8,434	4,289	8,155	4,133	7,701	4,016	8,788	4,425
345	8,746	4,406	8,635	4,393	8,448	4,286	8,033		8,874	4,456
690	8,820	4,435	8,748	4,434	8,691	4,442	8,404	4,320	8,907	4,467
1,035	8,873	4,456	8,791	4,439	8,710	4,512	8,572	4,368	8,928	4,490
1,725	8,905	4,515	8,821	4,470	8,783	4,467	8,652	4,444	8,973	4,510
2,415	8,926	4,545	8,884	4,480	8,793	4,440	8,703	4,397	8,983	4,526
3,105	8,936	4,553	8,862	4,502	8,834	4,472	8,743	4,422	9,017	4,530
4,140	8,956	4,533	8,892	4,526	8,886	4,492	8,784	4,433	9,062	4,549
5,170	8,977	4,529	8,987	4,559	8,895	4,514	8,792	4,459	9,096	4,539

tering of large augite crystals. It has apparently been metamorphosed. This tabulation shows several features that are characteristic of rocks in general. First, the increase in velocity with pressure is very rapid at the lower pressures and increases more slowly thereafter. Part of this is undoubtedly due to the closing up of pore space, thus forcing individual crystals into better contact. The effect of temperature is also much larger at the low pressures. This rock shows a fairly regular variation with temperature but most rocks, as will be shown, tend to change somewhat erratically with temperature. The room temperature run after the high-temperature run also shows a somewhat higher velocity. For this rock, the change is only about ½ of one percent but in many cases it is substantial. This effect is interpreted to indicate that subjection to pressure and temperature has compacted the rock.

This interpretation cannot always be applied, however. The corresponding data for a sample of granite from Barrifield, Ontario, is shown in Table III. This rock from thin section study has a granitic texture and is composed mostly of

quartz and microcline with a rose color probably due to iron stain during alteration. Here a room temperature run after the 100°C. and 200°C. runs shows a slight "improvement" but after the 300°C. run it is evident that the elastic properties have been drastically altered. In addition to a substantially lower velocity, the initial steep rise has disappeared as though all pore space had been filled and the material altered to a low velocity form. No apparent change in the sample could be detected.

This same effect has been observed in samples whose jackets failed and permitted the pressure fluid to penetrate the rock. In this sample, however, the gain in weight was only 42 mg. Thus the added fluid was at most only 4 parts in 10,000. When the jacket was removed no trace of kerosene could be detected.

TABLE III

Core #150, Sample 26

Description: Granite
Origin: Barriefield, Ontario

T—°C.	28		100		200		28		300		28	
P (bars)	V_D	V_R	V_D	V_R	V_D	V_R	V_D	V_R	V_R	V_R	V_D	V_R
20	5,640	2,866										
50	5,824	2,930	5,966	2,996	5,062	2,768	5,774	2,936			5,753	2,784
100	5,875	2,961	6,011	3,045	5,199	2,865	5,850	2,977			5,749	2,797
250	6,080	3,046	6,130	3,107	5,520	2,980	6,066	3,061	4,488		5,815	2,785
500	6,215	3,109	6,243	3,159	5,961	3,083	6,235	3,129	4,838		5,831	2,803
750	6,288	3,163	6,282	3,195	6,138	3,160	6,302	3,172	5,101		5,865	2,793
1,000	6,336	3,155	6,325	3,197	6,237	3,166	6,347	3,170	5,223		5,898	2,813
1,500	6,370	3,169	6,354	3,193	6,304	3,181	6,380	3,174	5,401		5,941	2,800
2,000	6,384	3,209	6,372	3,202	6,317	3,193	6,415	3,195	5,526		5,997	2,814
2,500	6,403	3,233	6,391	3,211	6,336	3,181	6,423	3,232	5,618		6,022	2,825
3,000	6,412	3,215	6,405	3,226	6,354	3,186	6,438	3,244	5,676		6,053	2,850
4,000	6,429	3,231	6,428	3,243	6,387	3,196	6,481	3,256	5,796		6,105	2,869
5,000	5,447	3,228	6,446	3,244	6,420	3,224	6,505	3,210	5,874		6,191	2,910

Table IV shows results in a sample of Solenhofen limestone. This sample again shows a slight "improvement" after the temperature runs. This sample did develop a very slight leak. After the runs the surface was slightly discolored and a section showed that a thin surface layer about 0.05 cm thick had been altered. This is also shown by the data. No 01 arrival could be detected at 300°C, and on the return to room temperature. We have observed that a layer of material around the cylindrical boundary of the core with a velocity somewhat less than that of the rock tends to destroy the transformation necessary to give 01. A copper jacket 0.012 inch thick has no apparent effect. A neoprene jacket over the length of the core reduces the transformed wave below detectibility.

Figure 4 shows to a still greater degree some of the effects discussed above. This is a sample of Pierre shale from the vicinity of Limon, Colorado. The original core was taken from a subsurface depth of 111 feet. The sample was jacketed and placed in the pressure chamber. Initially no energy was transmitted. This is a common occurrence and usually is due to the end caps of the jacket not being seated. The pressure was raised slowly and at 750 bars a fairly strong

arrival appeared and remained visible as the pressure was lowered to 50 bars. The velocity at this pressure was then 2,675 meters/sec as compared to 1,875 meters/sec as determined by The Carter Oil Company from seismic field work. This difference is undoubtedly due partly to the fact that the sample was carried up to a substantial pressure before the velocity was measured; however it is highly probable that this is also partly due to dispersion. As will be shown, this sample compacted substantially under pressure and it is probable that in its original state frequencies in the megacycle band were very strongly absorbed.

Starting from the 50 bar point, the pressure was increased step by step and the resulting velocities measured. At 1,000 bars, the velocity was 3,325 m/sec.

TABLE IV

Core #134, Sample 24

Density: 2.656
Description: Solenhofen Limestone.
Origin: Bavaria, Germany.

T—°C	25		100		200		300		25	
P (bars)	V_D	V_R	V_D	V_R	V_D	V_R	V_D	V_R	V_D	V_R
0	5,974	2,879							6,028	
100	6,000	2,952	5,892	2,949	5,756	2,890	5,547		6,046	
250	6,009	2,977	5,909	2,957	5,764	2,906	5,629		6,059	
500	6,025	2,991	5,925	2,962	5,784	2,928	5,691		6,080	
750	6,038	2,999	5,932	2,972	5,799	2,930	5,721		6,088	
1,000	6,051	3,006	5,949	2,970	5,814	2,937	5,744		6,105	
1,500	6,063	3,013	5,973	2,974	5,838	2,942	5,771		6,127	
2,000	6,079	3,018	5,989	2,986	5,853	2,944	5,802		6,143	
2,500	6,100	3,023	6,005	2,994	5,880	2,947	5,816		6,165	
3,000	6,108	3,026	6,017	2,998	5,892	2,948	5,844		6,177	
4,000	6,123	3,046	6,023	3,004	5,910	2,961	5,866		6,212	
5,000	6,134	3,040	6,037	3,004	5,928	2,974	5,892		6,218	

On lowering the pressure to 750 bars, the velocity continued to increase reaching 3,385 m/sec. This almost certainly indicates a time lag, i.e., the 1,000 bar pressure was not held long enough to establish equilibrium. The pressure was then returned to 50 bars and the velocity measured as 3,000 m/sec. Runs II and III were then made from 50 bars to 1,000 bars and return. On these runs the sample showed little hysteresis, i.e., the velocity at a given pressure was nearly the same going up or down. The velocities for these runs are very nearly the same. This would indicate that the rock was stabilized for this pressure range. Run IV was then made carrying the pressure up to 3,000 bars. The velocities duplicate runs II and III very accurately up to 1,000 bars. Beyond 1,000 bars the velocity increases rapidly to a value of 3,970 m/sec at 2,000 bars and then slowly to 4,120 m/sec at 3,000 bars. On the run down the sample shows some hysteresis

down to 2,000 bars but beyond this point continues along almost the same straight line to a value of 3,915 m/sec at 750 bars. At this pressure one of the electrical connectors broke and the sample had to be removed. Later, run *V* was made. Here it became evident that a true first arrival was not readable below 500 bars and hence data is plotted beginning at this point. This run gives every

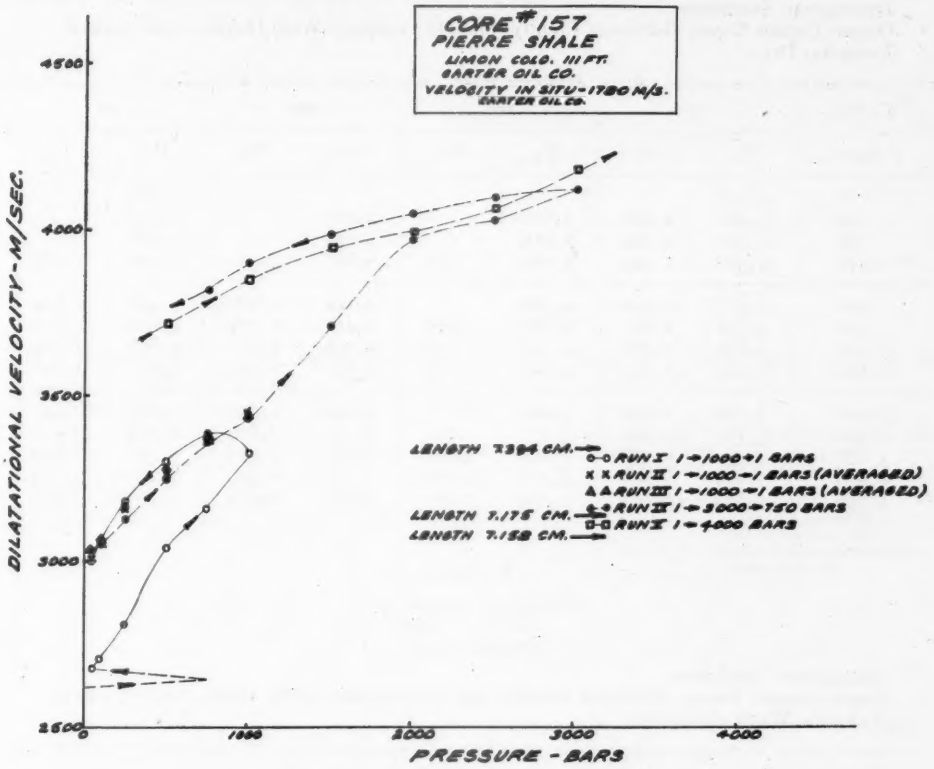

FIG. 4. V_D vs. Pressure Pierre Shale.

evidence of duplicating the original. At 3,000 bars, the connection was again broken and the sample had to be removed. It is evident, however that the sample has been fairly well stabilized for the range 0–3,000 bars. The original length of the sample was 7.394 cm. After the first run to 3,000 bars it was 7.175 cm. and after the second run it was 7.158 cm. The diameter changed proportionally. The density increased from 2.20 to 2.42.

Table V shows data taken with a sample of sandstone from the Caplen Dome, Galveston County, Texas, subsurface depth 6,500–7,000 feet. The porosity was measured as 5.1 percent. The core was dried and the standard runs taken. As would be expected in a material high in quartz, the temperature effect is

small. V_D curves rise rapidly at first and finally very slowly with pressure. V_R changes very slowly. Poisson's ratio is low but increases substantially with pres-

TABLE V

Core #154, Sample 29
Density 2.543°
Porosity 5.1%

Description: Sandstone.
Origin: Caplen Dome, Galveston County, Sun Oil Company Well, Depth, 6,500–7,000 ft.
Remarks: Dry.

T—°C	27		100		200		30	
P (bars)	V_D	V_R	V_D	V_R	V_D	V_R	V_D	V_R
0	3,672						2,963	
50	3,936	2,483	3,601		3,077		3,322	
100	4,042	2,514	3,819		3,295		3,586	
250	4,367	2,594	4,089	2,472	3,801		4,030	2,583
500	4,577	2,700	4,382		4,144	2,600	4,428	2,644
750	4,758	2,807	4,587	2,688	4,411	2,637	4,670	2,705
1,000	4,870	2,847	4,737	2,751	4,575	2,675	4,812	2,764
2,500	5,020	2,884	4,929	2,833	4,852	2,797	5,047	2,868
2,000	5,110	2,925	5,061	2,876	4,992	2,846	5,193	2,932
2,500	5,167	2,944	5,151	2,922	5,102	2,879	5,278	2,970
3,000	5,127	2,956	5,208	2,966	5,157	2,922	5,341	2,992
4,000	5,279	2,975	5,295	2,969	5,225	2,944	5,419	3,004
5,000	5,363	2,971	5,345	2,973	5,312	2,975	5,461	3,025

TABLE VI

Core #155, Sample 29
Density 2.606°
Porosity 5.1%

Description: Sandstone.
Origin: Caplen Dome, Galveston County, Sun Oil Company Well, Depth, 6,500–7,000 ft.
Remarks: Water saturated.

T—°C.	27		100		200		28	
P (bars)	V_D	V_R	V_D	V_R	V_D	V_R	V_D	V_R
0	4,453	2,319					4,487	
50	4,548	2,432	4,213				4,507	
100	4,462	2,687	4,196		3,789		4,536	
250	4,469	2,761	4,217		3,802		4,577	2,404
500	4,505	2,896	4,233		3,873		4,659	2,509
750	4,537	3,008	4,268		3,932		4,739	2,603
1,000	4,553	3,104	4,307		3,960		4,788	2,688
1,500	4,608	3,263	4,324		4,074		4,903	2,506
2,000	4,651	3,377	4,373		4,180		5,007	2,669
2,500	4,689	3,468	4,411		4,295		5,070	2,730
3,000	4,706	3,598	4,442		4,397		5,160	2,968
4,000	4,782	3,651	4,535		4,600		5,252	3,105
5,000	4,887	3,945	4,660		4,796		5,323	3,176

sure. The return to room temperature shows a small deviation from the original.

Table VI shows some data taken with a water saturated sample of the same material. The first room temperature run does not show the initial large rise in velocity. The reason for the 200°C. velocities rising above the 100°C. velocities is not evident. This together with the return to room temperature run would indicate that the sample had lost water. However, the sample lost no weight during the run so this explanation is not possible.

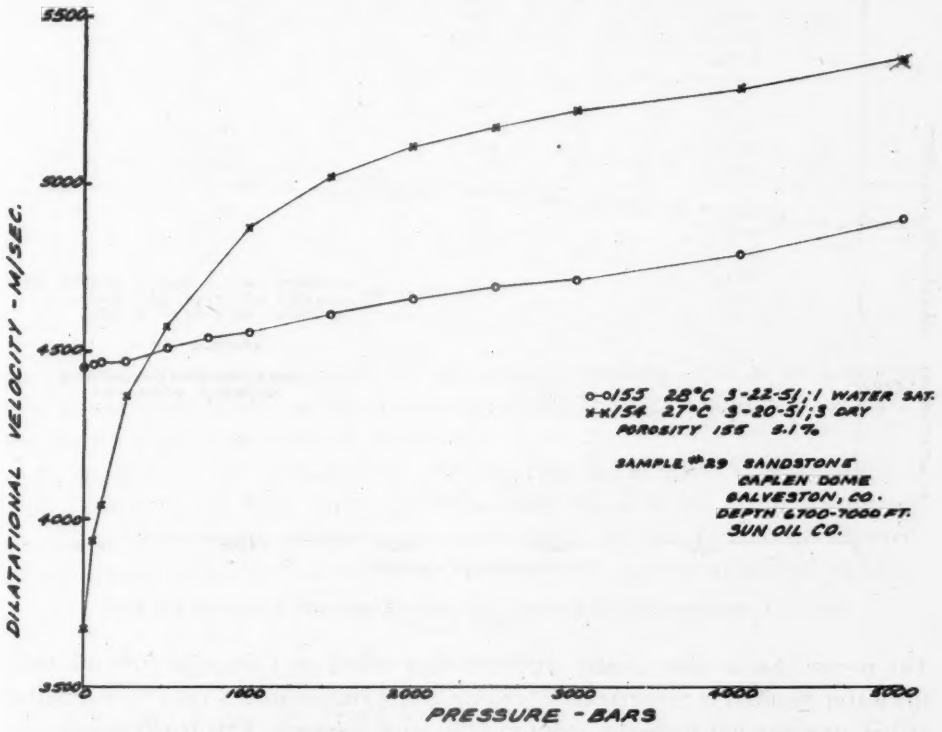

FIG. 5. Comparison V_D vs. Pressure Caplen Dome Sandstone, Saturated and Dry.

Figure 5 shows the initial room temperature runs for both the dry and saturated samples plotted together. In this material the water has increased substantially the velocity at low pressure and reduced largely the rate of increase with pressure. Qualitatively this checks former observations (Hughes and Jones, 1950) on igneous rocks in which oil was permitted to penetrate the rock. The curves may be explained by assuming that in the dry core the pulse is travelling alternately through rock and air. With increase in pressure the air space is closed up and the velocity is essentially that through solid rock. In the saturated core, the pulse is travelling alternately through rock and water. Water has a much higher velocity than air hence the initial velocity is higher. An increase in

pressure now, however, cannot close up the pore space and hence the initial velocity increases slowly with pressure.

The large change in room temperature velocity after the 200°C. run shown in Table VI can be ascribed to the water combining chemically with some material in the rock but it is almost impossible to adequately check this hypothesis. That the above explanation cannot always hold is shown by Figure 6. These data were taken on Solenhofen limestone. Core 133 was run saturated then dried and re-run.

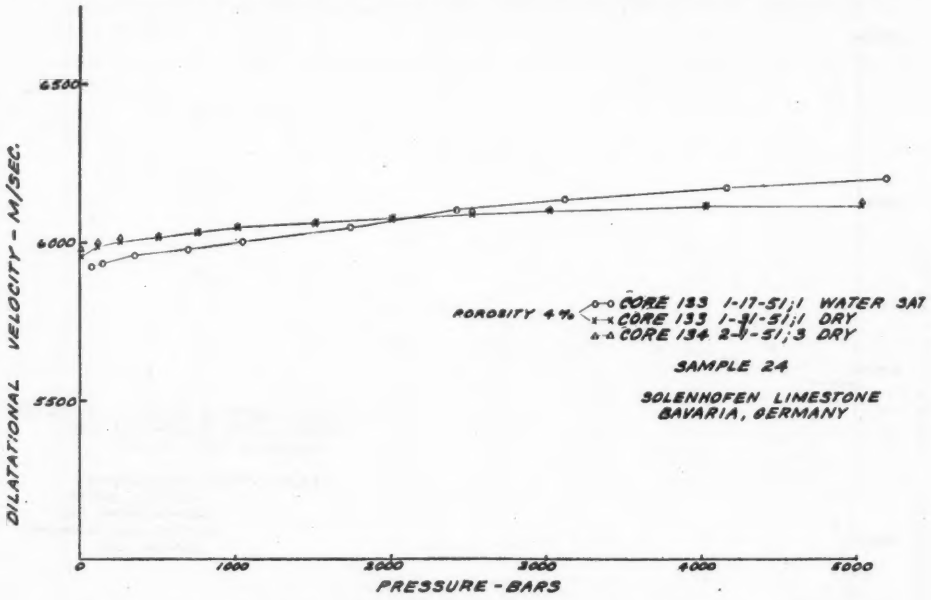

FIG. 6. Comparison V_D vs. Pressure Solenhofen Limestone, Saturated and Dry.

The re-run checks very closely with the data taken on Core 134, showing that the water resulted in no permanent change. Here the saturated velocity is smaller at low pressure but increases more rapidly with pressure. This is effectively the opposite of the behavior of the Caplen Dome sandstone.

The porosity of the Solenhofen limestone is about 4 percent and thus is very close to that of the Caplen Dome sandstone which is 5 percent. There is a great difference in permeability however. In our method of saturating the rock, it is placed in a glass tube and evacuated until warming it to about 100°C. gives no rise in pressure above 0.002 mm of Hg. It is then sealed off and the tube immersed in distilled water that has been boiled and pumped to remove gas. The tip of the tube is broken permitting water to enter the tube and sample. The tube is then placed in the pressure cylinder and the pressure slowly raised to 5,000 bars and held for about one hour. The pressure is then slowly released. If any water is forced into the sample by pressure it will be revealed by an equal amount of kerosene in the tube after removal from the pressure cylinder. The Caplen Dome

TABLE VII

Core #141, Sample 32
Density 2.514

Description: Travis Peak Sandstone.
Origin: Lassater Field, Marion County, Texas, 7,571 ft. subsurface, Magnolia Oil Company Well.

T—°C.	27		100		27	
P (bars)	V_D	V_R	V_D	V_R	V_D	V_R
0	3,726				3,926	
50	3,951		4,222		4,099	
100	4,113		4,367		4,224	
250	4,581		4,767		4,724	
500	5,086		5,048		5,183	
750	5,310		5,310		5,342	
1,000	5,373		5,354		5,382	
1,500	5,427		5,402		5,403	
2,000	5,457		5,433		5,433	
2,500	5,483		5,468		5,459	
3,000	5,500		5,484		5,495	
4,000	5,533		5,518		5,514	
5,000	5,553		5,557		5,552	

sample was effectively saturated by atmospheric pressure, that is, no kerosene entered the tube. With the Solenhofen limestone, however, almost all the water was placed in the sample by the pressure.

It appears to the authors that two separate mechanisms operate when a fluid is placed in the rock. First, the replacement of air or gas in the pore space leads to behavior similar to that shown by Figure 5. This explanation is checked by our former work (Hughes and Jones, 1950). Here, however, the fluid was No.

TABLE VIII

Core #122, Sample 27

Description: Danby Marble
Origin: Rutland, Vermont.

T—°C.	26		100		200	
P (bars)	V_D	V_R	V_D	V_R	V_D	V_R
70	5,866	2,823	4,536	2,512	4,296	2,336
140	6,060	3,071	4,944	2,673	4,653	2,550
345	6,250	3,104	5,819	2,947	5,326	2,750
690	6,501	3,147	6,290	3,061	5,938	2,965
1,035	6,551	3,170	6,409	3,104	6,235	3,055
1,725	6,621	3,195	6,542	3,125	6,395	3,090
2,415	6,651	3,118	6,576	3,138	6,436	3,101
3,100	6,665	3,209	6,585	3,145	6,460	3,106
4,140	6,673	3,209	6,602	3,146	6,468	3,106
5,170	6,660	3,254	6,621	3,133	6,474	3,096

TABLE IX

Core #151
Density 2.739

Description: Argillaceous Limestone (70% $CaCO_3$)
Origin: Barnet Farms A-1. 9,900–9,903 ft. Perpendicular to bedding, Upton County, Texas. Shell Oil Company Well.

T—°C.	27		100		200		27		100		200		28	
P (bars)	V_D	V_R	V_D	V_R	V_D	V_R	V_D	V_R	V_D	V_R	V_D	V_R	V_D	V_R
0													5,831	3,077
50	5,710	3,043	5,621		5,434	2,908	5,819	3,075	5,738	3,024			5,856	3,124
100	5,742	3,061	5,647		5,469	2,940	5,847	3,089	5,746	3,044	5,470	2,896	5,881	3,131
250	5,814	3,104	5,709		5,483	2,956	5,905	3,134	5,789	3,056	5,565	2,930	5,919	3,150
500	5,896	3,126	5,780		5,671	3,006	5,960	3,173	5,846	3,087	5,663	3,026	5,969	3,178
750	5,946	3,123	5,837		5,733	3,027	6,003	3,189	5,895	3,113	5,733	3,043	6,007	3,180
1,000	5,980	3,134	5,890		5,772	3,055	6,032	3,190	5,920	3,134	5,780	3,075	6,042	3,170
1,500	6,053	3,158	5,931	3,196	5,836	3,099	6,071	3,212	5,870	3,147	5,848	3,124	6,071	3,213
2,000	6,059	3,188	5,792	3,344	5,884	3,116	6,092	3,247	6,012	3,166	5,888	3,120	6,101	3,230
2,500	6,086	3,213	5,996	3,386	5,924	3,118	6,112	3,253	6,073	3,211	5,929	3,135	6,113	3,253
3,000	6,106	3,219	6,029	3,143	5,954	3,131	6,125	3,265	6,057	3,203	5,961	3,146	6,125	3,265
4,000	6,135	3,222	6,032	3,181	5,988	3,176	6,167	3,260	6,090	3,228	6,006	3,185	6,167	3,263
5,000	6,173	3,237	6,099	3,175	6,037	3,175	6,192	3,265	6,131	3,125	6,042	3,193	6,169	3,244

10 motor oil, the pressure was limited to 1,000 bars, and the temperatures were 200°C. or less. In addition, however, there is certainly the possibility of chemical change in the material due to interaction of the fluid and rock. In almost every instance of a jacket leaking the leak has occurred on the 300°C. run at high pressure. In every instance this penetration of hot kerosene under high pressure has very substantially lowered the velocity. With a core of Danby marble the rock became very soft and could be crumbled easily. It would no longer transmit any energy in our range. We have also observed two very porous sandstones of 9 percent and 28 percent porosity that would transmit no signal at all when

TABLE X

Core #152
Density 2.731

Description: Argillaceous Limestone (70% $CaCO_3$) Parallel to Bedding.
Origin: Barnet Farms A-1, 9,900–9,903 feet, Upton County, Texas. Shell Oil Company Well.

T—°C.	26		100		200		30	
P (bars)	V_D	V_R	V_D	V_R	V_D	V_R	V_D	V_R
0							6,107	3,191
50	6,028	3,030	5,987	3,166	5,926	3,131	6,114	3,210
100	6,046	3,134	6,020	3,177	5,931	3,145	6,119	3,214
250	6,088	3,178	6,056	3,189	5,954	3,162	6,156	3,226
500	6,131	3,205	6,104	3,209	5,995	3,168	6,187	3,248
750	6,155	3,226	6,134	3,220	6,036	3,201	6,224	3,254
1,000	6,173	3,239	6,164	3,225	6,047	3,217	6,236	3,262
1,500	6,241	3,262	6,182	3,252	6,088	3,233	6,248	3,282
2,000	6,278	3,282	6,212	3,259	6,111	3,232	6,265	3,284
2,500	6,296	3,291	6,223	3,256	6,140	3,229	6,290	3,283
3,000	6,321	3,290	6,234	3,265	6,151	3,233	6,328	3,295
4,000	6,344	3,296	6,257	3,274	6,160	3,244	6,351	3,294
5,000	6,368	3,291	6,293	3,282	6,207	3,253	6,368	3,295

saturated. The 9 percent core gave good data when dried. The 28 percent core would still transmit no energy when dry.

Table VII shows dilatational velocities for the Travis Peak sandstone. The 01 arrival could not be identified and hence V_R could not be computed. This sample showed a porosity of 9 percent. Saturated with water it would transmit no detectible energy. The data of Table VIII were taken after drying. The velocities are very close to those measured on the Caplen Dome sandstone despite the great difference in origin.

Several runs have been made on the Danby marble most of which were invalidated by leaks. This material, which is apparently a very pure marble, shows great changes with only slight leaks. Table VIII shows the best data that have been obtained.

Tables IX and X show data on two cores cut from an argillaceous limestone well core. These cores were cut one perpendicular and one parallel to the bedding

TABLE XI

VELOCITIES AT SELECTED DEPTHS

P—Bars T—°C.	Depth	$V-M/S$	Dunite Twin Sisters 123	Granite Quincy 164	Granite Barriefield 150	Quartzite Cheshire 147	Marble Danby 122	Limestone Solenhofen 134	Ss. Caplen Dome—6,700 Ft. Dry 154	Ss. Caplen Dome—6,700 Ft. Wet 155	Limestone Argillaceous ⊥ Bed 151	Limestone Argillaceous II Bed 152	Shale Calcareous ⊥ Bed 116
90 25°	.33 km 1,080 ft	V_D V_R σ	8,603 4,185 .345	5,880 2,944 .333	5,850 2,977 .325	5,995 3,894 .135	5,963 2,947 .338	6,000 2,952 .340	4,042 2,594 .204	4,536	5,742 3,061 .301	6,046 3,134 .316	3,887
750 100°	2.8 km 9,200 ft	V_D V_R σ	8,770 4,437 .328	6,169 3,132 .326	6,282 3,195 .326	6,043 3,903 .142	6,290 3,061 .346	5,932 2,972 .333	4,587 2,688 .238	4,268	5,837 3,087 .306	6,134 3,220 .310	4,315 2,733 .183
1,620 200°	6.1 km 20,000 ft	V_D V_R σ	8,783 4,467 .326	6,228 3,157 .327	6,354 3,193 .331	5,833 3,841 .127	6,395 3,090 .348	5,838 2,942 .330	4,852 2,797 .251	4,074	5,836 3,099 .304	6,088 3,233 .310	4,513 2,817 .184
2,540 300°	9.4 km 30,800 ft	V_D V_R σ	8,703 4,397 .329			5,585 3,627 .135		5,816					

from very closely neighboring positions. The data shows a definite anisotropy, with the higher velocity parallel to the bedding. This checks qualitative earlier observations, but this data is particularly good because of the close spacing of the cores.

CONCLUSIONS

A résumé of data on several rocks is presented in Table XI. The V_D, V_R, and Poisson's ratio σ have been computed for various depths using a temperature increase with depth of 30°C./km. This gradient was chosen as an approximate average. The increase of V_D with depth down to 9,000 feet is very much less than is usually observed in the field. Below 9,000 feet the velocities increase very slowly or even decrease slightly.

A reasonable explanation would appear to be that in our measurements insufficient time has elapsed to attain equilibrium. This time could, of course, be extremely long. Observation thus far shows no detectable change in a few hours with the exception of the one point of the Pierre shale (Figure 4).

The values of Poisson's ratio are very reasonable and in general change but little with depth. The ratio for the Cheshire quartzite (147) is slightly irregular. The values for the quartzite, sandstone (154), and shale (116) are substantially lower than the other rocks.

Samples 151 and 152 were cut from a single well core (Shell Oil Company, Barnet Farm A-1, 9,900 feet) perpendicular and parallel to the bedding. There is a substantial difference in the velocities. Our methods of computing V_R and σ are not valid for anisotropic materials and thus the values entered for these cores are for comparison only.

ACKNOWLEDGMENTS

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A SEISMIC WAVE GUIDE PHENOMENON*

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ABSTRACT

On one particular prospect in shallow water repetitive patterns appeared on short spread seismograms in such prevalence as to jeopardize identification of desired reflections. It is demonstrated that under favorable conditions, less restrictive than thought necessary heretofore, a layer of water comprises an effective wave guide for seismic energy propagation. Reinforcement fronts formed by multiple reflection of sound in water can develop into a set of waves completely overshadowing other seismic arrivals. With but minor modifications conventional wave guide theory applies.

Examples from the prospect are presented to illustrate various reinforcement patterns. Observed frequency characteristics, group velocity, and phase velocity magnitudes are investigated for normal modes of propagation.

INTRODUCTION

Oil prospecting over water has revealed sound transmission characteristics either absent or less obvious on land. Among these can be mentioned repeated bursts of energy traceable to oscillations of the explosion bubble, simple multiple reflections between bottom and surface of the water, offside reflections from objects near the surface, and wave guide propagation which usually involves dispersion.

This last characteristic, wave guide propagation, stems from reflections between top and bottom of the water layer. The high frequency of first energy arrivals associated with long range direct waves in shallow water comprises one manifestation. Seismic observations reveal that this initial high frequency wave marks the beginning of a band of waves whose frequency rapidly decreases. These waves of continuously lower frequency persist until terminated by the Airy phase. The theory for the case of a liquid bottom has been given by Pekeris and for a solid bottom by Press and Ewing. In both these cases the propagation is due to total reflection within the liquid layer involving rays whose angle of incidence at the bottom lies between the critical angle and the grazing angle.

In this paper we deal with a closely related phenomenon involving more nearly vertical incidence and very gradual dispersion. No doubt in most areas low reflection coefficients in effect at the bottom of water layers prevent the development of this wave guide action. The example here described came to light through two special circumstances which favor real or apparent sustained reinforcement at practically constant amplitude level. First, over the seismic prospect which yielded the observations, the bottom of the water layer is smooth and

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composed of rock, producing a high reflection coefficient even for normal incidence; second, automatic volume control on the amplifiers increases the gain for waves whose energy decreases due to leakage during a large number of reflections. This gives the impression of a long train of waves of almost constant amplitude.

Previous theoretical work can readily be extended to include the case of only partial reflection at the bottom. It will be shown that in this case there is a limiting frequency for which the group velocity approaches zero and the phase velocity approaches infinity. Normal mode propagation in simply the water layer produces seismograms showing waves which could easily be mistaken for a long series of excellent reflections from deep horizons.

OBSERVATIONS

Characteristic Seismograms

Since our introduction to the problem came through observation of seismograms on which regular reflection arrivals were obscured by water-transmitted energy, perhaps this discussion can be best introduced in a similar manner. Consider first then the seismogram illustrated in Figure 1, which may at first give the erroneous impression that it is a very good regular reflection record. The seismogram illustrates, among other things, the unusually long time throughout which wave amplitudes persist at levels that, because of automatic volume expansion, appear to be practically constant. Certain characteristics of the seismogram appear to repeat. A check on time intervals between them establishes periodicity. Further examination shows that almost every detail of trace movement is repeated over period after period. Essentially there is very little on the record beyond the features contained in a single interval such as the one indicated by marks.

Figure 2 shows a seismogram which, from the standpoint of seismic prospecting, is more obviously hopeless than the first and therefore less treacherous. This second seismogram is simpler, consisting mostly of a long train of nearly sinusoidal waves. It develops that Figures 1 and 2 involve the same pattern of propagation; they differ only in the particular normal modes present.

Empirical Formulas

Examination of a number of seismograms over a particular offshore prospect indicates frequency of this wave motion is closely related to depth of water. Trial shows the frequency formula

$$f = 3V/4H \tag{1}$$

describes the oscillations in Figure 2 well within the limit of accuracy with which water depth H is determined by sounding line or fathograms. Here V is velocity of sound transmission in water. In general, on many other records,

$$f = (2n - 1)V/4H \tag{2}$$

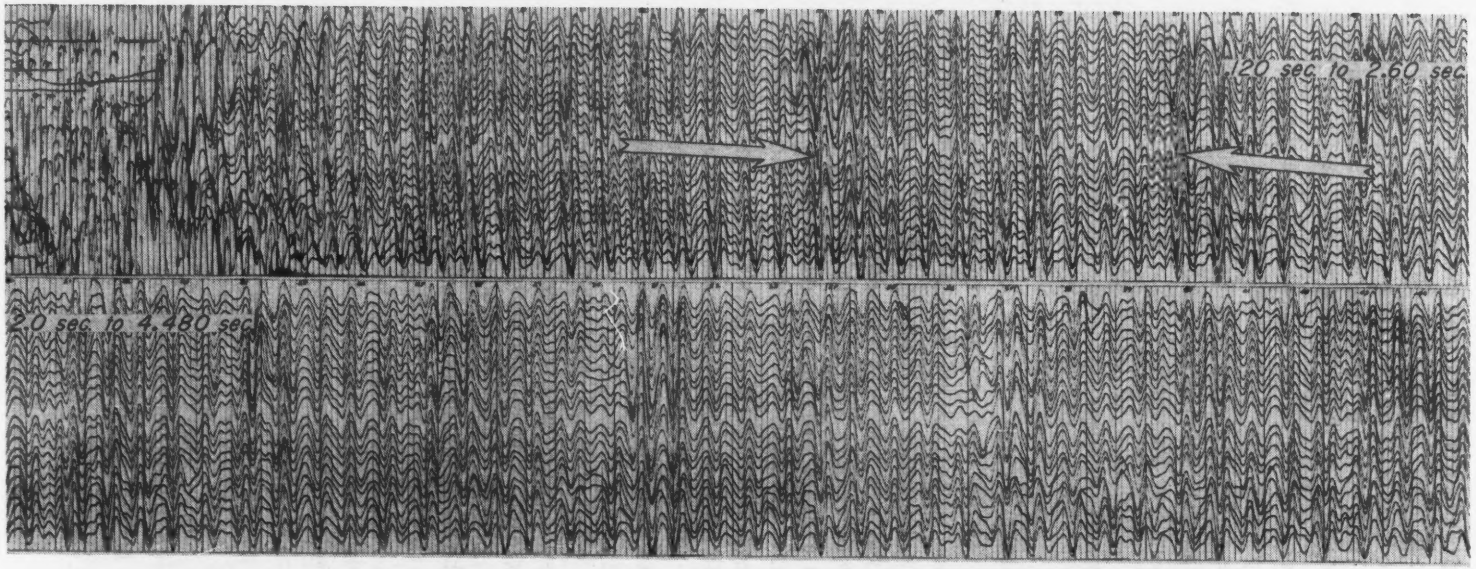

FIG. 1. 20 to 60 cycle per sec seismogram showing remarkable periodicity. Depths: Water, 148 ft; seismometers, 10 ft; 50 lb dynamite, 5 ft. Distances from shot: Trace 1, 1,090 ft; Trace 12, 665 ft; Trace 24, 1,285 ft. Recording spread: 2,000 ft.

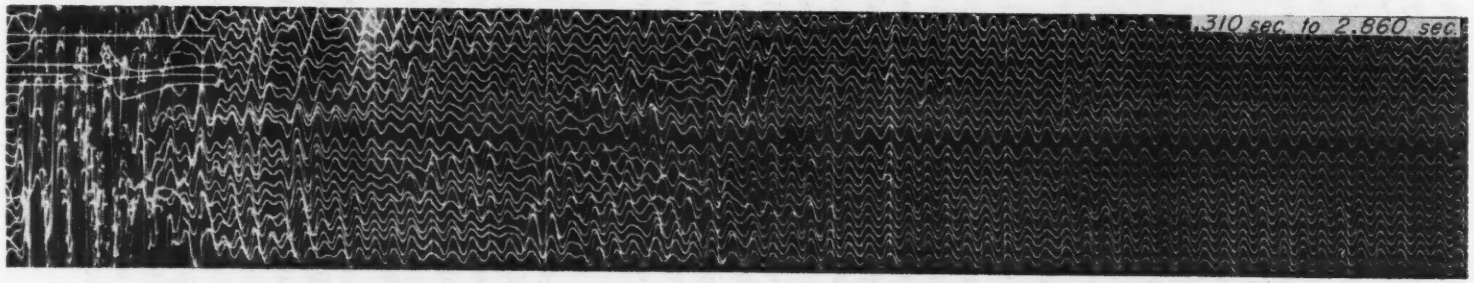

FIG. 2. 16 to 40 cycle per sec seismogram showing almost pure sine waves. Depths: Water, 132 ft; seismometers, 8 ft; 50 lb dynamite, 5 ft. Distances from shot: Trace 1, 2,405 ft; Trace 12, 2,155 ft; Trace 24, 2,340 ft. Recording spread: 2,000 ft.

where $n=1, 2, 3 \ldots$, fits the observations well. These are essentially the frequencies of resonance in vibrating bars clamped at one end or in organ pipes closed at one end.

Examples

Figure 3 shows a resonant record of relatively low frequency—about $22\frac{1}{2}$ cycles per second. Applying the formula for the second normal mode, $n=2$ in

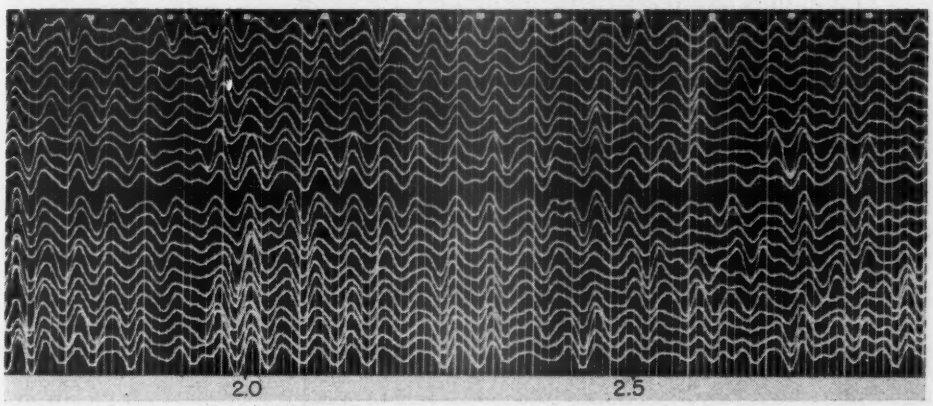

FIG. 3. 16 to 40 cycle per sec seismogram showing second odd harmonic or second normal mode of vibration. Depths: Water, 165 ft; seismometers, 8 ft; dynamite, 5 ft. Distances from shot: Trace 1, 2,555 ft; Trace 12, 2,275 ft; Trace 24, 2,480 ft. Recording spread: 2,000 ft.

Equation (2), and using 5,000 feet per second for propagation velocity gives $H=166$ feet. The fathometer reading was 165 to 167 feet. Figure 4 shows resonance in about 50 feet of water. Frequency here is 26.8 cycles per second. Computing depth, assuming the fundamental mode of vibration, gives 47 feet. Evidently the fourth normal mode appears in Figure 5; the 51 cycle frequency

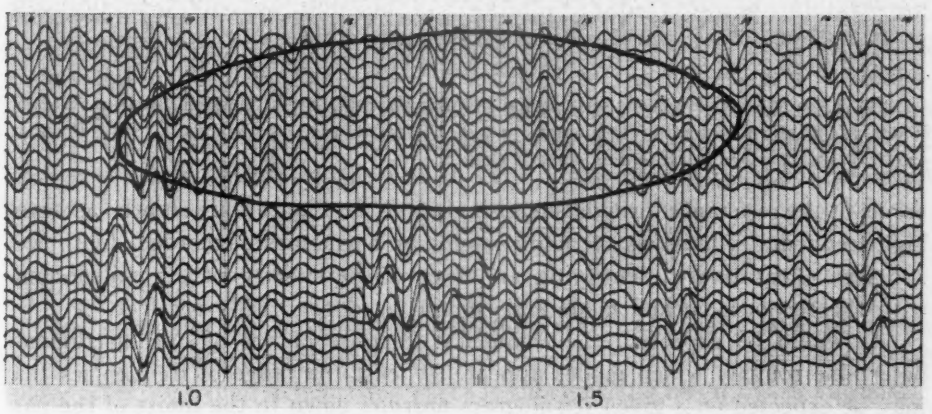

FIG. 4. 16 to 60 cycle per sec seismogram showing fundamental or first normal mode of vibration. Depths: Water, 53 ft; seismometers, 8 ft; dynamite, 5 ft. Distances from shot: Trace 1, 1,015 ft; Trace 12, 420 ft; Trace 24, 1,165 ft. Recording spread: 2,000 ft.

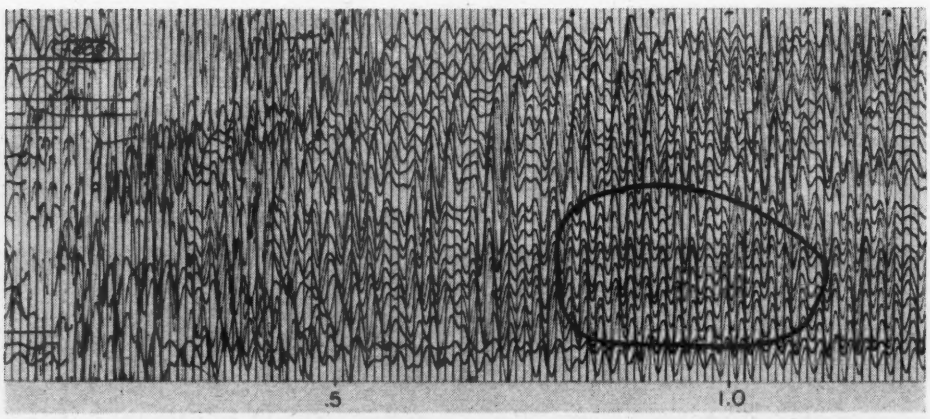

FIG. 5. 20 to 60 cycle per sec seismogram showing the fourth normal mode of vibration. Depths: Water, 164 ft; seismometers, 10 ft; dynamite, 5 ft.

applied in the appropriate formula gives 172 feet for H. The sounding records indicate a water depth of about 165 feet. In Figure 6 one finds the fifth normal mode. In deep water even extremely high frequencies recorded with wide pass

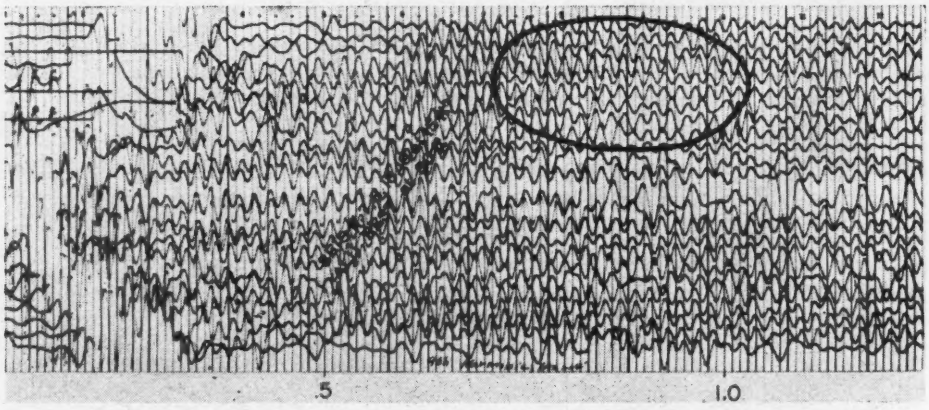

FIG. 6. 16 to 60 cycle per sec seismogram showing the fifth normal mode of vibration. Depths: Water, 214 ft; seismometers, 30 ft; dynamite, 214 ft. Distances from shot: Trace 1, 1,180 ft; Trace 12, 500 ft; Trace 24, 1,070 ft. Recording spread: 2,000 ft.

bands fit the resonance formula surprisingly well. In Figure 7 are shown sustained high frequency vibrations of many modes or harmonics. Recorded depth was 106 feet. Tentatively identifying an observed periodicity of 4.3 milliseconds with the eleventh normal mode and computing depth yields 113 feet.

As would be expected, the frequency response curves of our instruments determine roughly which modes appear. At least the range of frequencies that may be expected on a given seismogram narrows down to the limits of the pass band used. Although generally harmonics lying within the pass band are repre-

sented on a seismogram, it is sometimes difficult to account for the predominance of some and the absence of others. A typical frequency response curve appears in Figure 8. The arrow tips under the curve indicate a sequence of modes corresponding to the water depth above which the seismogram shown at the right was shot. On this record one can identify the third and fourth normal modes, which lie in the frequency range receiving optimum amplification.

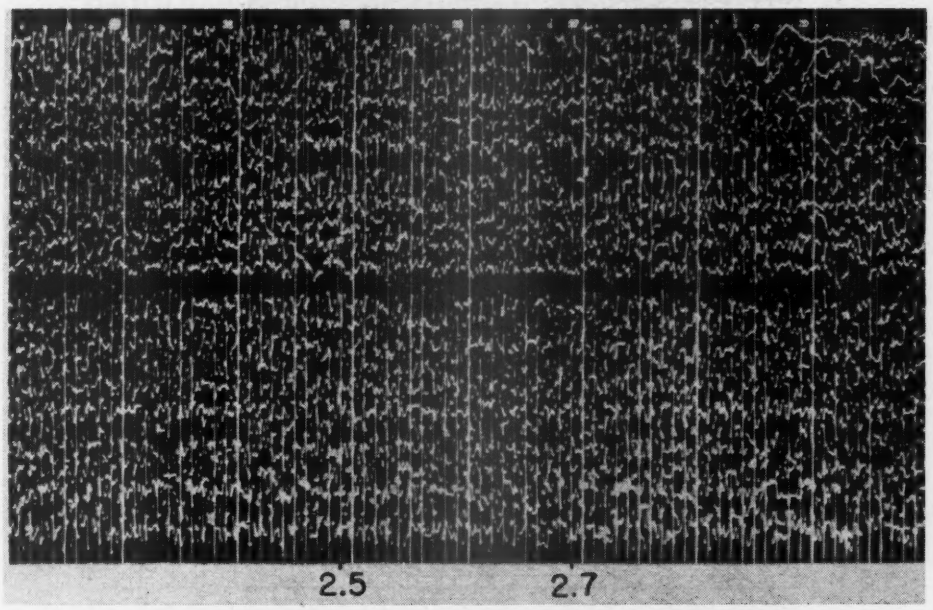

FIG. 7. Unfiltered seismogram showing various higher harmonics. Depths: Water, 106 ft; seismometers, 8 ft; dynamite, 5 ft. Distances from shot: Trace 1,2530 ft; Trace 12, 2,160 ft; Trace 24, 2,065 ft. Recording spread: 2,000 ft.

Figure 9 shows a portion of a seismogram obtained in 248 feet of water with a very flat uniform bottom. The cutout fitted to the top traces is a mathematically computed curve in which third, fourth and fifth normal modes were computed from the frequency formula and simply added. One can easily see that the curve applies almost equally well to any appropriate part of the seismogram segment shown.

THEORY

General Remarks

The unusually high multiples of reflections within the water layer offer evidence that reflection coefficients are close enough to unity so that even after many reflections their attenuating effect is substantially offset by an automatic increase in amplifier gain. Within the range of observations we have no specific data on amplitude level—only the illusion that oscillations continue practically

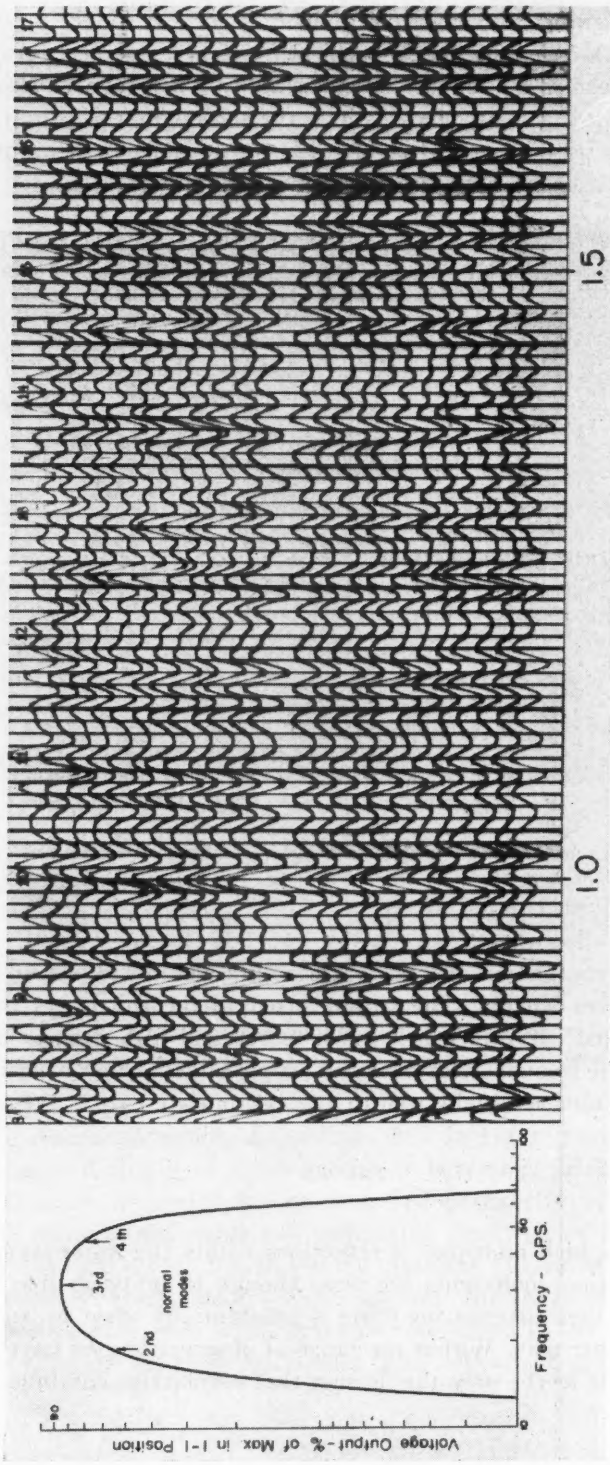

FIG. 8. Frequency response curve on a filter setting which on the seismogram at the right admitted third and fourth normal modes. Water depth: 192 ft.

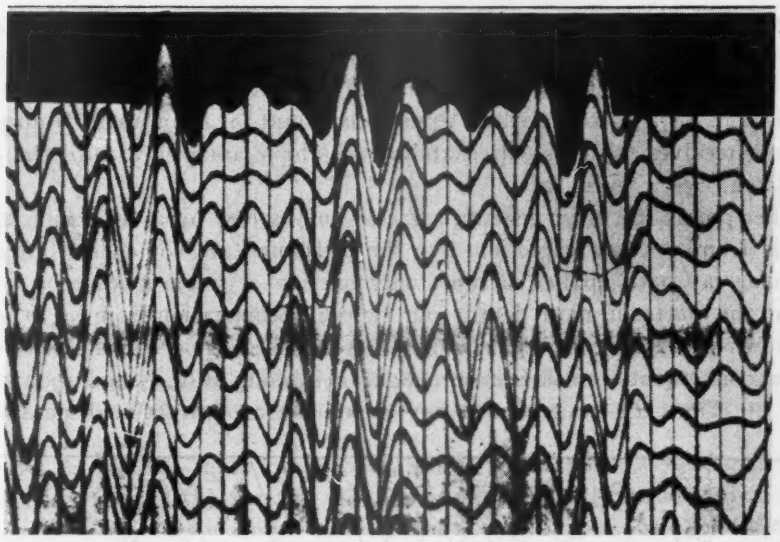

FIG. 9. The cutout at the top represents a mathematically computed curve of a combination of third, fourth, and fifth normal modes of vibration in water 248 ft deep. Note correlation with the actual seismogram below it.

undiminished. In first consideration of theory on an elementary level, then, the situation may as well be considered without reference to the effect of reflection coefficients, wave divergence, diffraction and other factors affecting attenuation.

Repetitive Arrivals of a Pulse

In this discussion we shall consider the shot a point source at (o, d) in an appropriately placed rectilinear coordinate system (x, z) with $z=o$ representing the surface of the water and $z=H$ representing a level bottom.

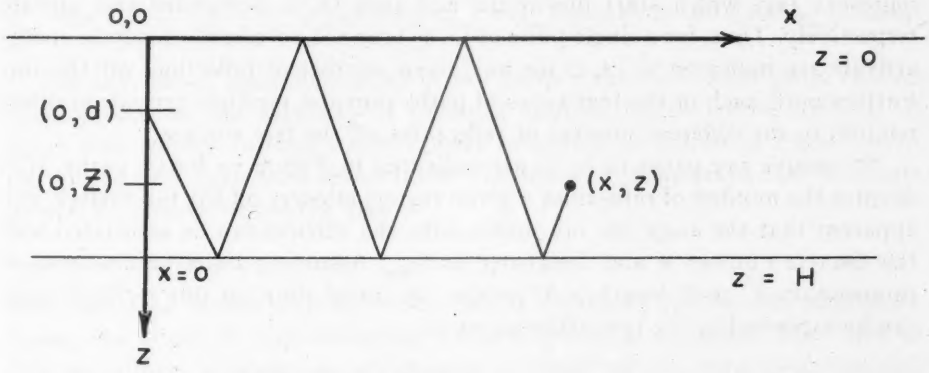

FIG. 10. Rays from (o, d) to (o, Z) multiple reflected at top and bottom of water layer and a particular ray path from (o, d) to (x, z) involving two reflections off the free surface.

Along $x=o$, a vertical line through the shot point, normal incidence applies upon reflection of the pulse at the boundaries of the water layer. It follows from the law of reflections that through successive reverberations the ray path of a pulse is here retraced repeatedly. A particular point (o, Z) in water H units deep therefore receives the pulse alternately from above and below until the energy dies down. See Figure 10.

Other points, (x, z) in general, are also bombarded by a succession of pulse arrivals from a single explosion, but the mechanics are somewhat different. A particular ray path applies at most only once, at a single instant of time. To present the matter in more detail, four types of propagation from (o, d) to (x, z) are shown in Figure 11. The classification is based upon the direction of the vertical component of wave front propagation initially at (o, d) and upon arriving at (x, z). Thus, P_d designates a ray which starts upward and passes (x, z)

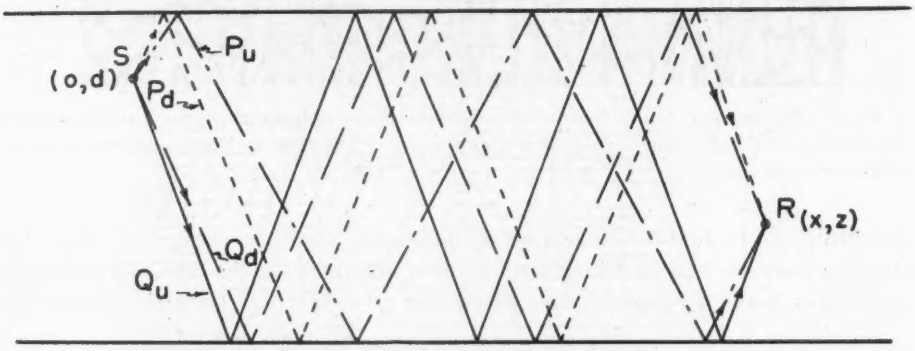

FIG. 11. Four types of ray paths from (o, d) to (x, z): P_d, initially upward, terminally downward propagation; P_u, initially upward, terminally upward; Q_d, initially downward, terminally downward; Q_u, initially downward, terminally upward propagation.

downward; P_u, a ray which starts upward and passes (x, z) upward; Q_d and Q_u represent rays which start downward and pass (x, z) downward and upward respectively. Thus, for a single pulse at (o, d) four not necessarily separate energy arrivals are indicated at (x, z) for any given number of reflections off the top. Furthermore, each of the four types of paths provides multiple arrivals in direct relation to the different number of reflections off the free surface.

Successive ray paths to (x, z) are indicated in Figure 12 for Q_d paths. If m denotes the number of reflections a given ray experiences off the top surface, it is apparent that the angle the ray makes with the vertical can be associated with the discrete number m and designated as $\theta_{Q_{dm}}$. Assuming a constant velocity of propagation V, path length is Vt where t is travel time, so this incident angle can be expressed in the two following ways:

$$\theta_{Q_{dm}} = \tan^{-1} \frac{x}{2mH - d + z} = \sin^{-1} \frac{x}{Vt}. \tag{3}$$

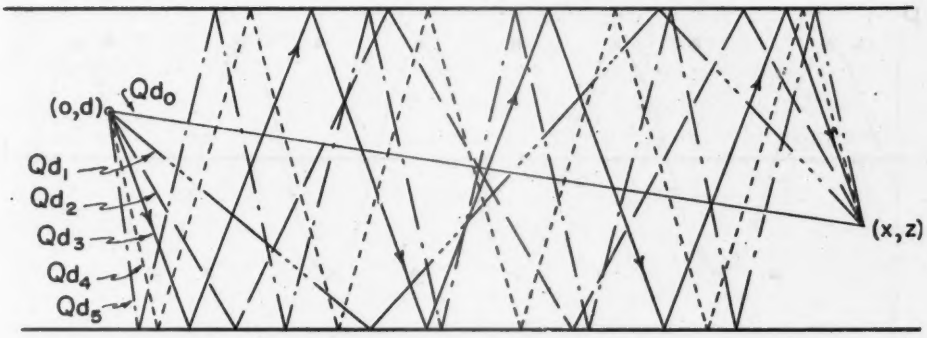

FIG. 12. The Q_d wave is schematically illustrated by ray diagrams for one through five reflections off the free surface between (o, d) and (x, z)—that is for $m=1, 2, 3, 4$, and 5 respectively.

Figure 12, as well as these expressions, shows convergence of successive rays through (x, z) toward the vertical as a limiting direction. $\theta_{m+1}-\theta_m$ thus becomes increasingly small. Ray length corresponding to $\theta_{Q_{dm}}$ is also $(2mH-d+z)\cos\theta_{Q_{dm}}+x\sin\theta_{Q_{dm}}$.

Since similar statements apply for the Q_{um}, P_{dm}, and P_{um} rays the situation may be summarized as follows:

Ray Designation	*Angle of Incidence*	*Travel Time*	*Path Length*
P_{dm}	$\theta_{P_{dm}}=\tan^{-1}\dfrac{x}{2(m-1)H+d+z}$	$t_{P_{dm}}=x/V\sin\theta_{P_{dm}}$	$Vt_{P_{dm}}=[2(m-1)H+d+z]\cos\theta_{P_{dm}}+x\sin\theta_{P_{dm}}$
P_{um}	$\theta_{P_{um}}=\tan^{-1}\dfrac{x}{2mH+d-z}$	$t_{P_{um}}=x/V\sin\theta_{P_{um}}$	$Vt_{P_{um}}=[2mH+d-z]\cos\theta_{P_{um}}+x\sin\theta_{P_{um}}$
Q_{dm}	$\theta_{Q_{dm}}=\tan^{-1}\dfrac{x}{2mH-d+z}$	$t_{Q_{dm}}=x/V\sin\theta_{Q_{dm}}$	$Vt_{Q_{dm}}=[2mH-d+z]\cos\theta_{Q_{dm}}+x\sin\theta_{Q_{dm}}$
Q_{um}	$\theta_{Q_{um}}=\tan^{-1}\dfrac{x}{2(m+1)H-d-z}$	$t_{Q_{um}}=x/V\sin\theta_{Q_{um}}$	$Vt_{Q_{um}}=[2(m+1)H-d-z]\cos\theta_{Q_{um}}+x\sin\theta_{Q_{um}}$

(4)

For any one of these four types of ray paths some convenient pulse characteristic, such as the extremes of pressure, plotted for successive arrivals at (x, z) with respect to time would appear somewhat as shown in Figure 13. A 180° phase shift with each reflection off the free surface requires that alternate arrivals be plotted below the axis.

Pulse Characteristics

In the case of the artificial seisms which produced the records previously shown, the origin of each disturbance was a dynamite explosion. The work of Cole and others indicates an underwater explosion of this type is propagated outward in the form of a pulse with roughly the shape illustrated in Figure 14, where pressure is indicated qualitatively with respect to time.

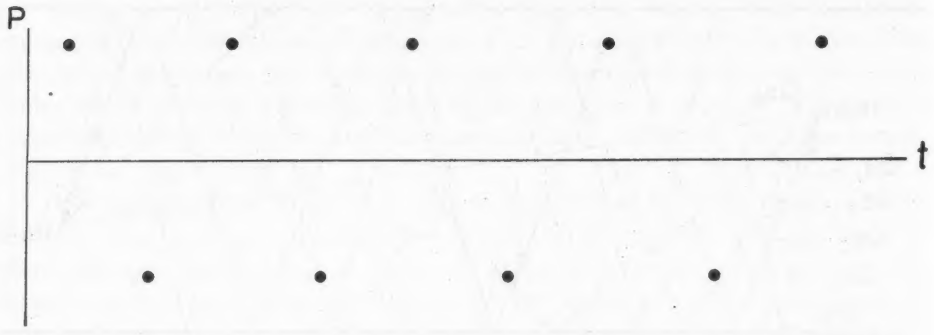

FIG. 13. Energy arrivals at (x, z) for a particular type ray for successively higher orders of multiple reflections. Pressure is plotted schematically with respect to travel time.

Experience and theoretical work by other writers indicates that this pulse is essentially a complex wave form representable by a continuous frequency spectrum of sine waves. In this discussion it will simply be assumed that the arrivals at any point (x, z) have the same general shape as the original pulse

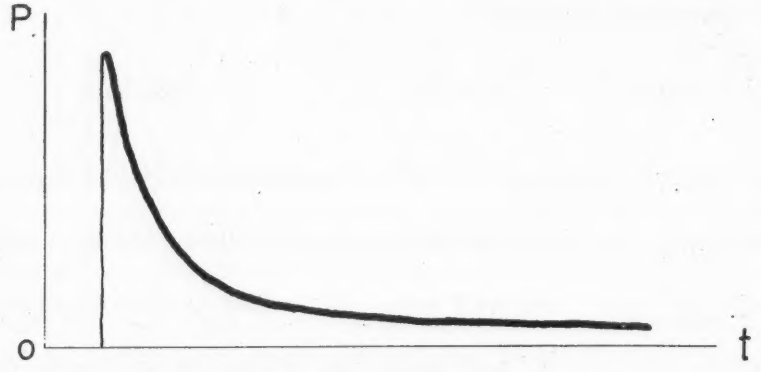

FIG. 14. Generalized pressure-time curve of an explosion.

for a few reflections—for small values of m. As m increases these arrivals are manifested by whatever frequency components are favored by interference effects between the multiply reflected waves and the frequency response of the recording system.

Wave Development

In line with this view on pulse characteristics one would then expect the multiple arrivals portrayed in Figure 13 to appear in the form of those wave components which fit the pulse arrival pattern. The lowest frequency range expected is shown fitted to these arrivals in Figure 15. Development of even harmonics of this wave will evidently be prevented by the alternations in phase.

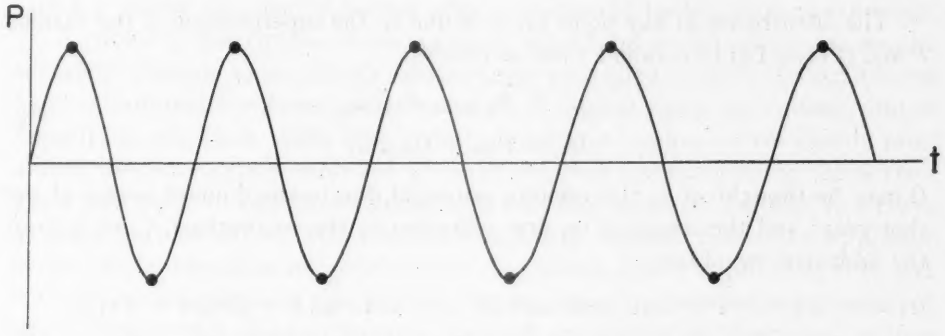

FIG. 15. Energy arrivals of Figure 13 fitted with an appropriate wave form.

Odd harmonics may, however, be fitted as well as the fundamental. The combination of eligible wave components may therefore be a quite complex wave form. Thus, Figure 9 shows the form developing out of the combination of three particular odd harmonics or normal modes. To investigate this wave development further let us express the four types of travel in the form of velocity potentials of the expected waves at any point (x, z) at a time t after m reflections from the free surface.[1]

$$\begin{aligned}
P_{dm} &= A(-1)^m\epsilon^{m-1} \exp i2\pi\{x \sin\theta + [2(m-1)H + z + d]\cos\theta - Vt\}/L,\\
P_{um} &= A(-1)^m\epsilon^m \exp i2\pi\{x \sin\theta + [2mH - z + d]\cos\theta - Vt\}/L,\\
Q_{dm} &= A(-1)^m\epsilon^m \exp i2\pi\{x \sin\theta + [2mH + z - d]\cos\theta - Vt\}/L,\\
Q_{um} &= A(-1)^m\epsilon^{m+1} \exp i2\pi\{x \sin\theta + [2(m+1)H - z - d]\cos\theta - Vt\}/L,
\end{aligned} \tag{5}$$

where $\theta = \sin^{-1} x/Vt$, L is the wave length measured along the oblique ray path, A is a variable amplitude factor which is left unevaluated, and ϵ is the bottom reflection coefficient depending on θ and the elastic properties of the two layers involved. Phase shifts during m reflections off the free surface are accounted for by the factor $(-1)^m$.

Let

$$\delta = \exp i2\pi(2H\cos\theta)/L = \exp i\pi(4H\cos\theta)/L. \tag{6}$$

Then

$$\begin{aligned}
P_{dm} &= A(-1)^m\epsilon^{m-1}\delta^{m-1} \exp i2\pi[x \sin\theta + (z + d)\cos\theta - Vt]/L,\\
P_{um} &= A(-1)^m\epsilon^m\delta^m \exp i2\pi[x \sin\theta - (z - d)\cos\theta - Vt]/L,\\
Q_{dm} &= A(-1)^m\epsilon^m\delta^m \exp i2\pi[x \sin\theta + (z - d)\cos\theta - Vt]/L,\\
Q_{um} &= A(-1)^m\epsilon^{m+1}\delta^{m+1} \exp i2\pi[x \sin\theta - (z + d)\cos\theta - Vt]/L.
\end{aligned} \tag{7}$$

[1] These wave expressions could, with minor modifications, be applied to direct analysis of other characteristics besides velocity potential, such as pressure, displacement, or vertical component of particle velocity.

The disturbance at any point (x, z) is due to the superposition of the various P and Q rays. Let us combine these as follows:

$$\begin{aligned} \Omega_d &= P_{d(m+1)} + Q_{dm} \\ \Omega_u &= P_{um} + Q_{u(m-1)} \end{aligned} \tag{8}$$

Ω may be thought of as the velocity potential due to the doublet source of the shot point and the image of its first reflection in the top surface. Carrying out the additions we obtain:

$$\begin{aligned} \Omega_d &= -A(-1)^m\epsilon^m\delta^m i \sin(2\pi d\cos\theta/L)\exp i2\pi[x\sin\theta + z\cos\theta - Vt]/L, \\ \Omega_u &= A(-1)^m\epsilon^m\delta^m i \sin(2\pi d\cos\theta/L)\exp i2\pi[x\sin\theta - z\cos\theta - Vt]/L. \end{aligned} \tag{9}$$

Constant factors have been included in the unevaluated factor A. Ω_d and Ω_u will both contribute to the disturbance at any one point. Their combined effect is $\phi=\Omega_d+\Omega_u$, or

$$\phi = A(-\epsilon\delta)^m \sin(2\pi d\cos\theta/L)\sin(2\pi z\cos\theta/L)\exp i2\pi[x\sin\theta - Vt]/L, \tag{10}$$

where constant factors have again been included in A.

The waves given by ϕ for m reflections interfere with those of ϕ for $m+1$ reflections. Reinforcement occurs if $\phi_m+\phi_{m+1}$ is a maximum or when the quantity $1-\epsilon\delta=1-\epsilon\exp i2\pi 2H\cos\theta/L$ is a maximum. This condition is fulfilled for those wave lengths which satisfy the equation

$$2\pi 2H\cos\theta/L = (2n-1)\pi \tag{11}$$

where $n=1, 2, 3\ldots$ The wave length factor is then

$$L = (4H\cos\theta)/(2n-1). \tag{12}$$

Here the integer n determines the harmonic or the normal mode of propagation and the dependence of θ upon t establishes L as a function of t.

Since $\delta=-1$ under the condition for optimum wave development we may write

$$\phi_n = A\epsilon^m \sin\left(\frac{2\pi}{L}z\cos\theta\right)\sin\left(\frac{2\pi}{L}d\cos\theta\right)\exp i2\pi(x\sin\theta - Vt)/L. \tag{13}$$

With the aid of Equation 12 velocity potential can be written

$$\phi_n = A\epsilon^m \sin[(2n-1)\pi z/2H]\sin[(2n-1)\pi d/2H]\exp i2\pi(x\sin\theta - Vt)/L. \tag{14}$$

This expression represents a progressive wave traveling in the water layer in the x direction with dispersive characteristics, since $L=f(t)$, and with a standing wave pattern between the surface and bottom which is independent of θ. Nodal planes are consequently parallel to the surface. The summation of the velocity potentials ϕ_n for all modes, from $n=1$ to ∞, and over as large a range of m as applies, gives the over-all disturbance at any point or instant of time. The

factor ϵ^m shows the effect of partial refraction into the bottom at each reflection.

A complete description of the resulting wave form would, of course, require a careful analysis of amplitude relationships embodied in $A\epsilon^m$. No record was kept of automatic volume gain expansion. A typical figure on volume control capacity is 10^5. Thus, while high amplitude particle motion arrives shortly after a shot, amplifier gain is throttled to the extent that trace motion on the seismogram may have an amplitude comparable with that produced by only 10^{-5} times as much particle motion with controls completely released. Since true amplitude ratios can be identified on observations only within limits as broad as this, and since elastic constants of the bottom were not measured, it was not considered worthwhile at this stage to identify expected amplitudes by theoretical expressions.

Dispersion Characteristics

The rate of progress of a particular phase is identifiable by the relation

$$\frac{d\frac{2\pi}{L}(x \sin\theta - Vt)}{dt} = 0. \tag{15}$$

Expressing L and θ in terms of x and Vt and differentiating $(v^2t^2-x^2)^{1/2}$ leads to the phase velocity expression

$$c = V/\sin\theta. \tag{16}$$

Group velocity measures the rate of progress of the wave group associated with each wave length. From simple geometry in this case, or from the general formula

$$U = c + Kdc/dK \tag{17}$$

where $K=(2\pi/L)\sin\theta$, one can identify group velocity as

$$U = V \sin\theta. \tag{18}$$

Since $\sin\theta = x/Vt$, we also have

$$U = x/t. \tag{19}$$

For each n or each normal mode of propagation frequency

$$f = V/L = (2n-1)V/4H \cos\theta. \tag{20}$$

For reasons explained earlier we limit our discussion to values of θ in the range $\theta_c \geqq \theta \geqq 0$ where θ_c is the critical angle of reflection at the bottom, the angle with the vertical whose sine is the ratio of water velocity to the velocity of underlying material. The corresponding range of frequency is $f_c \geqq f \geqq f_0$ where f_c is the cutoff frequency beyond which the earlier theoretical discussions apply (see Pekeris or Press and Ewing, 1950) and f_0 is the cutoff frequency given by $(2n-1)V/4H$ for $\theta=0$. See Equation 2.

INTERPRETATION OF THEORY

An impulsive point source of sound in a water layer generates spherical waves which undergo numerous multiple reflections from the surface and a level bot-

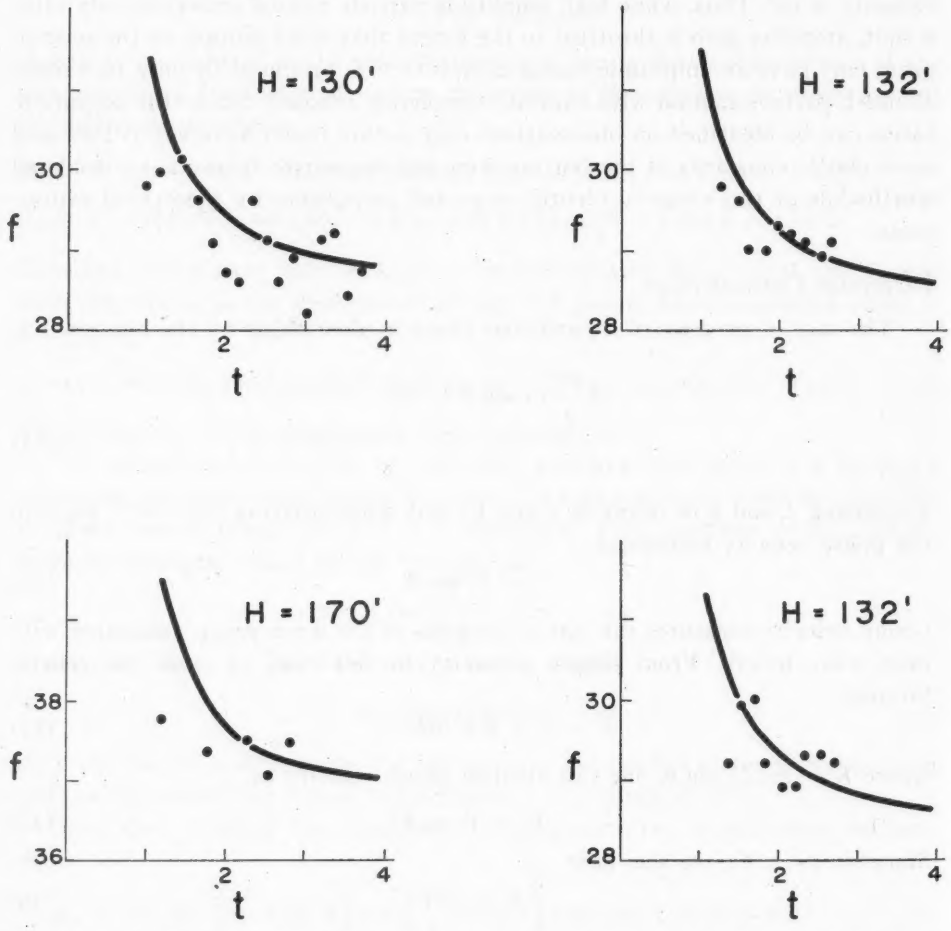

FIG. 16. Each graph shows wave frequency plotted with respect to arrival time for a particular record. Each plotted point represents an average of several actual observations. The smooth curves fitted to collections of average points represent the frequencies predicted by theory.

tom. The disturbance at any distant point is obtained by the superposition of all the waves arriving at this point by the different ray paths indicated.[2] The

[2] In fact a spherical wave can be represented by a sum of component plane waves with appropriate amplitude factors (Press and Ewing, 1950; Officer, 1951). Our elementary discussion can in a sense be considered an analysis of these plane waves leaving out the amplitude factor.

result of the combination is a single disturbance which travels outward from the source and vertically has a standing wave pattern of motion from the surface to the bottom.

The initial disturbance generated by an underwater explosion can be analyzed into a broad continuous frequency spectrum. However, only particular frequencies are reinforced according to normal mode propagation theory, and these are identified by Equation 20. Significantly, it is members of this set of frequencies that are observed. See Figure 16. Because these frequencies are a function of the incident angle θ, and in turn time t, for any particular x, they can be assigned characteristic velocities. The concepts of phase and group velocities were then introduced to distinguish between the velocity with which a constant phase proceeds and the velocity with which a given frequency proceeds forward.

A description of the system of waves associated with values of θ greater than the critical angle has been given elsewhere (Press and Ewing, 1950), where it was shown that the last waves of this group arrive at a time corresponding to propagation with a velocity of about 0.6 V. Following this group an infinitely long train of waves arrive associated with normal mode propagation for values of θ smaller than the critical angle. If one focuses attention on any given mode (by means of filters for example) the frequency of the waves decreases slowly with time, the rate of decrease becoming more and more gradual as time increases and as the cutoff frequency for $\theta=0$ is approached. Phase and group velocity, however, are quite sensitive, approaching infinity and zero respectively as θ approaches 0.

These waves are attenuated due to partial refraction at each reflection from the bottom. For a given shot detector distance, the number of reflections m increases as θ decreases, hence attenuation due to reflection increases as travel time increases. For a given travel time and distance frequencies of the various modes have the ratios 1:3:5:7: $\cdots$. To a large extent the resultant wave pattern actually recorded is determined by interference between the various modes admitted within the filter pass bands used.

The pressure or velocity field generated by an underwater explosion can be discussed most simply in terms of the pressure fields of the component normal modes. Expressions for pressure p or vertical particle velocity $\dot{w}$ can be derived from Equation (14) and the relationships

$$p = -\rho \frac{d\phi}{dt} \qquad \dot{w} = \frac{\partial \phi}{\partial z}.$$

Thus the vertical variation of pressure and particle velocity are respectively given by the factors

$$\sin\left[\left(\frac{2n-1}{2}\right)\pi \frac{z}{H}\right] \quad \text{and} \quad \cos\left[\left(\frac{2n-1}{2}\right)\pi \frac{z}{H}\right]$$

$$n = 1, 2, 3, \cdots. \qquad (21)$$

The following conclusions are evident from these equations:

(1) The surface $z=0$ is a nodal plane in pressure or an antinodal plane in vertical particle velocity for all frequencies and modes.

(2) The bottom $z=H$ is an antinodal plane in pressure and a nodal plane in vertical particle velocity for all frequencies in all modes.

(3) There are $n-1$ nodal planes in pressure for all frequencies and modes beneath the surface located at depths given by

$$\frac{z}{H} = \frac{2}{2n-1}, \quad \frac{4}{2n-1}, \quad \frac{6}{2n-1}, \cdots, \quad \frac{2n-2}{2n-1} \qquad n = 1, 2, \cdots.$$

(4) There are n nodal planes in vertical particle velocity located beneath the surface at depths given by

$$\frac{z}{H} = \frac{1}{2n-1}, \quad \frac{3}{2n-1}, \quad \frac{5}{2n-1}, \cdots, \quad \frac{2n-1}{2n-1} \qquad n = 1, 2, 3, \cdots.$$

The above equations would indicate that the response to these waves of a hydrophone sensitive to pressure changes and a geophone sensitive to vertical particle velocity varies with depth because of the vertical standing wave pattern. Since the ideal location of a detector for elimination of these waves is at a nodal plane, the preceding criteria may be used to determine theoretically the best depth for locating detectors. A similar discussion may be given for charge location.

MISCELLANEOUS ASPECTS

It must be obvious that the preceding remarks about the observed multiple reflection phenomenon are essentially introductory. Vital aspects of the problem have not been adequately treated. Of these, amplitude has already been mentioned.

A study of reflections from plates of finite thickness might disclose the possibility of a more detailed description of bottom conditions than given. A. B. Wood in *A Textbook of Sound* indicates thickness of the reflector is quite an important factor. Certainly a complete discussion of the problem would include a consideration of possible reverberation in shallow solid or semi-solid layers below the water.

Effect of corrugations along the bottom or top of the water layer has been entirely neglected. Nevertheless, a complete understanding of reinforcement phenomena would require more attention to this point.

In localities where the bottom is rugged no periodicity was observed. Even gently sloping bottoms must radically modify the described dispersion pattern or prevent the development of resonance altogether. Poulter's interesting analysis of slope determination from multiple reflection behavior appears to offer a promising approach to a study of the effect of bottom relief. The fact that parallel plates comprise only one example of electromagnetic wave guides or cavity

resonators suggests that seismic counterparts may not be restricted to the simple example here described.

The assumption that velocity of propagation is constant appears to be justified in our example by the close fit between observations and theoretical predictions. If dimensions of the region considered were radically altered, variations in propagation velocity might be pertinent factors.

Finally, this most excellent example of a seismic wave guide suggests that there may be others less perfectly developed. Numerous instances of periodicity on reflection records have been experienced in land shooting. Some may bear an interesting relationship to the reinforcement example herein discussed.

Establishment of a sound wave guide requires, in general, that

(1) A source of sound energy provide essentially true continuous wave motion or pseudo-continuous wave motion through pulse reverberation.

(2) Boundary geometry, transmission characteristics, and reflection characteristics be favorable to the development of particular reinforcement waves progressing away from the shot.

SUMMARY

Among the different types of waves observed in seismic measurements over water we can include the normal mode propagation produced by constructive interference as described in various papers by Ewing, Pekeris, and Press. A particular example of this type of wave develops relatively close to the source of energy provided bottom conditions are favorable. Seismograms from a particular prospect show this phenomenon so pronounced that all normal reflections from underlying beds are completely lost.

At the shot point the resonant condition which develops is analogous to that which develops in an organ pipe closed at one end. The geometry of spherical waves multiply reflected at the boundaries of the water layer provides for a spreading of the resonant zone out from the shot point. This progressive growth is accompanied by dispersion which takes the form of gradual changes in dominant frequencies.

Geometry and terminology of electromagnetic wave guides applies very nicely to this particular instance of normal mode propagation. The body of shallow water herein described might therefore be termed a leaking wave guide.

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SEISMIC RECORD SECTIONS*

H. R. PRESCOTT†

ABSTRACT

A method is described whereby seismic records may be secured which have sufficient dimensional stability that a composite reprint of several records, from a continuous profile, when placed in proper sequence, yields a cross section of seismic arrivals. A method is described for entering corrected time scales on the seismic record section itself. Double recording is provided, with traces in transposed positions but alike in phase relation, which makes possible the construction of closed traverse sections. A few examples of the record section are shown and some uses suggested.

INTRODUCTION

There are times when the seismic interpreter strongly desires to see a continuous traverse of seismic records in composite form for critical study. More than this, the routine use of a scheme which produces a composite seismic arrival section can be made both desirable and convenient for the interpreter. One method of producing the record sections will be given.

APPARATUS FOR SECURING THE FIELD RECORD

Essentially, the seismic recording equipment is conventional in design with a few exceptions. The recording camera produces records of very uniform dimension along the time axis. This is accomplished by use of a synchronous motor drive in the camera, electronically tied to the timing source for stability. To allow high-quality reprints, transparent film is used. To provide a final composite section having a minimum width for convenience of routine study and final review, the width of the seismic record itself is held to less than that of conventional records. A width of two inches is currently in use. It is desirable that the quality of the optical traces be finer and sharper than is necessary on conventional records for the reason that the width of the record is restricted.

Although not an actual necessity for production of record sections, the use of double recording accomplishes some additional objectives. These objectives will be described later.

Figure 1 shows a field record produced by recording equipment intended for record section use including double recording. As currently practiced, the original double field record is four inches wide and the separate two inch wide records are later secured by splitting the original record. The traces on the halves of Figure 1 are alike in phase relation but are *transposed* in *position*, as diagrammatically indicated. For example, a specific channel indicated by the

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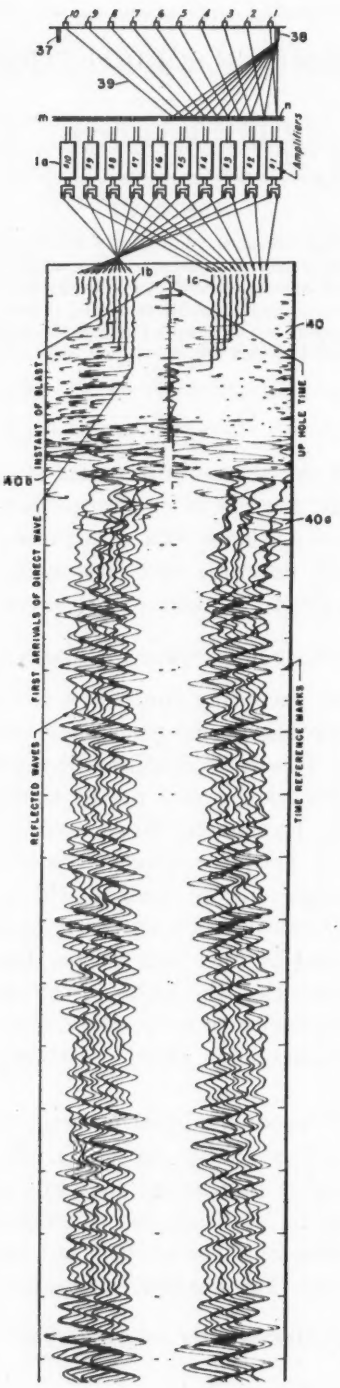

FIG. 1. Double recording where the traces on the halves are alike in phase relation but are transposed in position.

numeral 1a produces traces 1b and 1c of like polarity; but on one of the two halves it appears as the bottom trace, whereas on the other half it appears as the upper trace. This feature of transposed position of traces is maintained by choice as will be explained later.

The timing lines on the original field record are restricted to short 'tips' along the edges of the two inch records as shown by Figure 1. This leaves most of the record clear for later application of corrected time scales.

APPARATUS FOR PROCESSING THE FIELD RECORD

Although the camera which secures the field record may be quite precise in speed, the final record itself will show some dimensional variations between equal time intervals. The magnitude of the dimensional instability will depend on the material used, on the environmental humidity, and on the age of the record following photographic processing. It has been found that cellulose acetate film is generally sufficiently stable dimensionally for the purpose. The length will vary about one part per thousand for each ten percent change of relative humidity. After prolonged aging, the length may reduce nearly one percent. To obviate this instability, the following process has been adopted.

In the field office, the original record is positioned in a stretching frame and gently stretched to match carefully in length a set of timing lines etched on a zinc plate. Several zinc line etchings are available to provide a range of dimensional choices from areas of low relative humidity to areas of high humidity in order that the record need not be stretched unduly.

After the record is stretched to accurately match the zinc plate in use, cellulose acetate ink is applied by a brayer to the zinc line etching. Next, the record is superimposed to position properly the zinc scales for corrected times and the film record is pressed against the zinc line etching to receive an ink impression. The ink is applied to the back of the film in order that the timing scale marks may be removed by a solvent without disturbing the emulsion should it become desirable to erase them. Silver or orange-colored ink is used to contrast more readily with the black timing line 'tips' on the original film.

Figure 2 shows the process somewhat more in detail. Each of the numerals 23 and 24 indicates one half of a double record where the ground was occupied from one shotpoint to another and where a shot from each shotpoint was recorded. The numerals 21, 22, and 25 indicate in diagrammatic outline the position of the zinc line scales. The numeral 28 indicates the position of the instant of blast. On record 23 the correction of the computing trace 29 for weathering and elevation is 0.025 second. The zinc scale 21 was moved along the time axis until the zero mark coincided with a value of 0.025 second after the instant of blast. The times read along this scale are corrected values.

On record 23 the computing trace 30 bears a correction of 0.022 second. The zinc scale 25 was moved along the time axis until the zero mark came at 0.022 second. This scale then produces corrected times for the computing trace 30. The uncorrected time scales on the common edges of records 23 and 24, for ex-

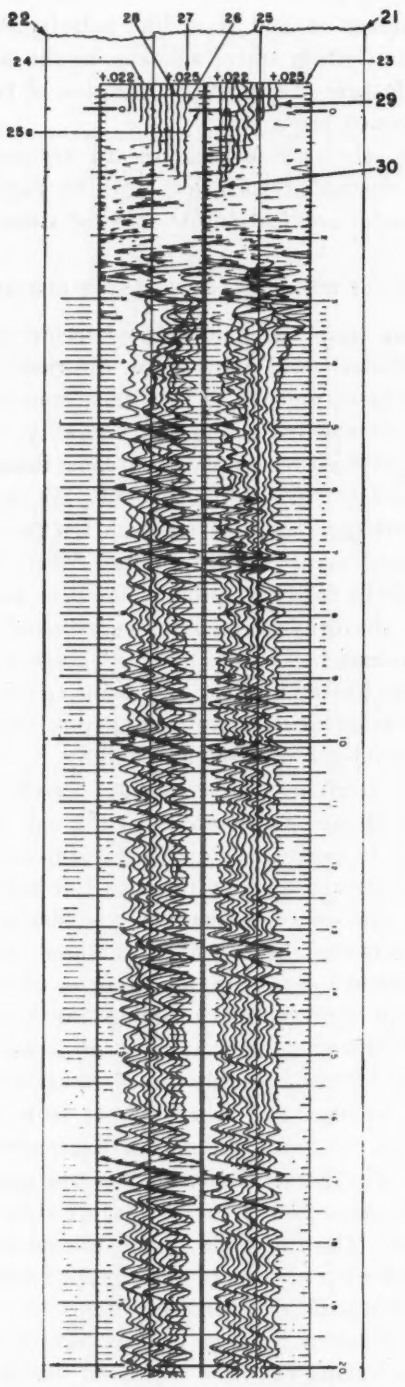

FIG. 2. The application of corrected time lines is illustrated on this pair of records obtained by occupying the surface between two shotpoints where a shot from each shotpoint was recorded.

ample, mismatch physically by the difference of the corrections applied, (0.025−0.022=0.003 second).

Similar treatment of the record 24 with zinc scales produces the result shown in Figure 2.

THE RECORD SECTIONS AND THEIR USE

After the original field record has received the ink impression of the corrected timing scale and the original double record has been separated into its halves, the records may be assembled in proper sequence to produce the record section as illustrated by Figure 3. Generally one day's work is assembled on a printing table and reprints secured, each of which is a single sheet. More than one day's work may be readily joined by pasting separate sheets together.

By choice, no selection of reflections is made on the original film, but selections are marked on the reprints. This permits fresh, unmarked reprints to be secured at will for new review efforts.

As interpretation of an assignment progresses, the reviewer may quickly obtain record section lines for study of the significant structural and stratigraphic features. He may readily prepare separately, in a single record section piece, closed loops for critical study of correlations and misclosures as illustrated by Figure 4. The transposed position of traces on the two halves of the original record allows assembly of continuous single pieces regardless of the orientation of recording equipment on the ground. The double recording illustrated by Figure 1 cannot be obtained by reverse printing of the original record or by a mirror image. To do so would transpose the position of the traces as desired but would invert the phase relation.

Although the double record anticipates the advantageous use of different equipment adjustments by choice, it has been interesting to observe that occasionally an interpreter can advantageously use a transposed record, on which there is no difference except transposition of the traces, for evaluation of a critical reflection selection. Although the records in this case would carry precisely the same traces, a reflection sometimes has a different appearance on the transposed record, presumably for the reason that the wavelet is not symmetrical.

Beyond the simplified type of record section illustrated by Figure 3 and further illustrated by Figures 4, 5, 6, 7, 8, and 9, other refinements can be made. For example, the arrivals have stepout times which tend to detract from cross-section use. Adjacent timing scales are staggered by the difference in correction, although this is not usually troublesome. The recording equipment can be designed, if desired, to produce the oscillograph type of record in the field and variable density traces (or variable area) at the same time. Reprocessing of the variable density record can be done by photo-electrical cells viewing variable density traces through a slit. The slits can be staggered in position to correct for weathering, elevation, and a variable dimension with time to compensate for normal stepout time of a selected velocity function. Such a reprocessed record in oscillograph trace form would then show the seismic arrivals in true relationship for all traces.

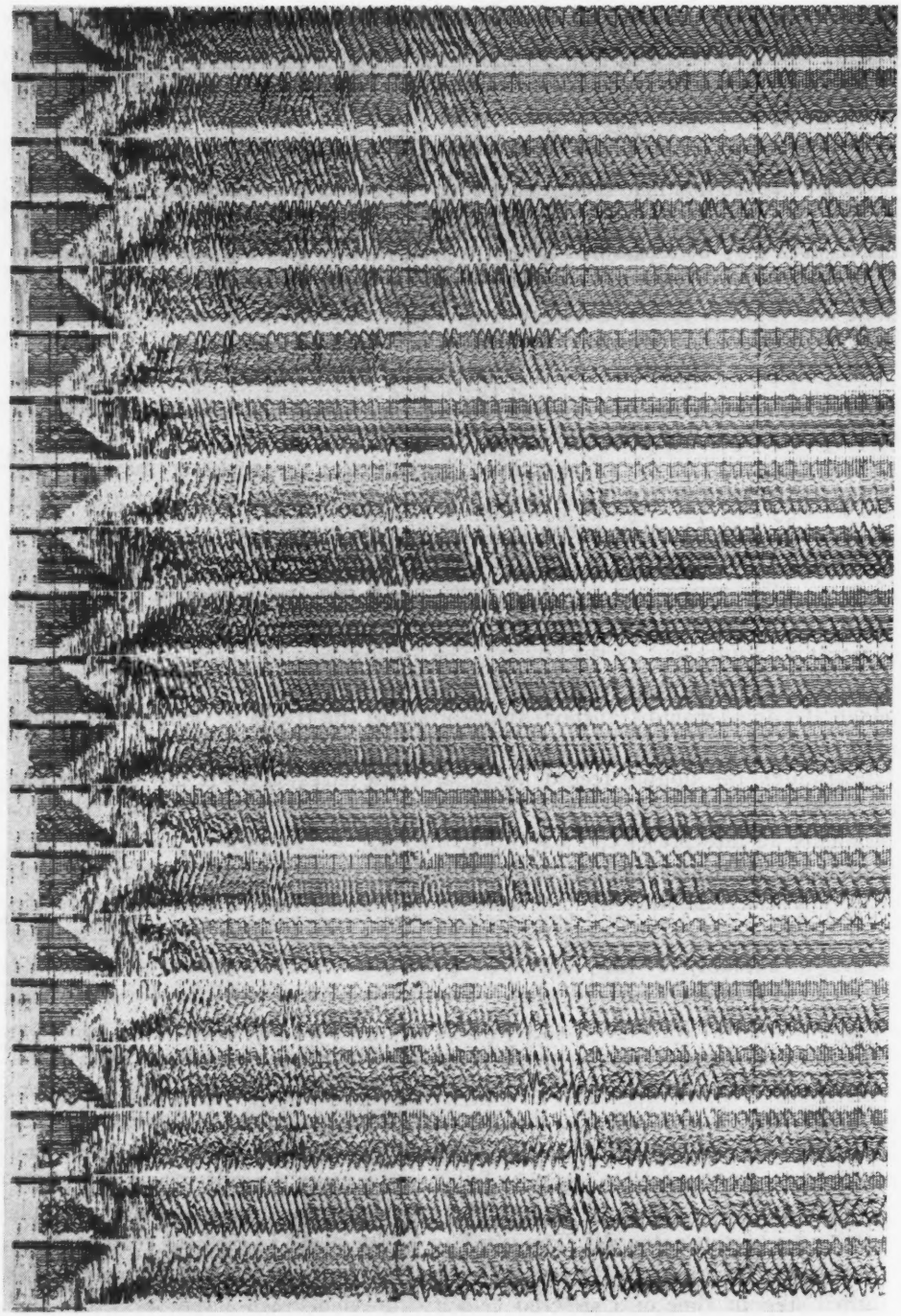

FIG. 3. A continuous straight line record section profile taken in southern Oklahoma showing prominent thickening toward the basin within the Pennsylvanian section.

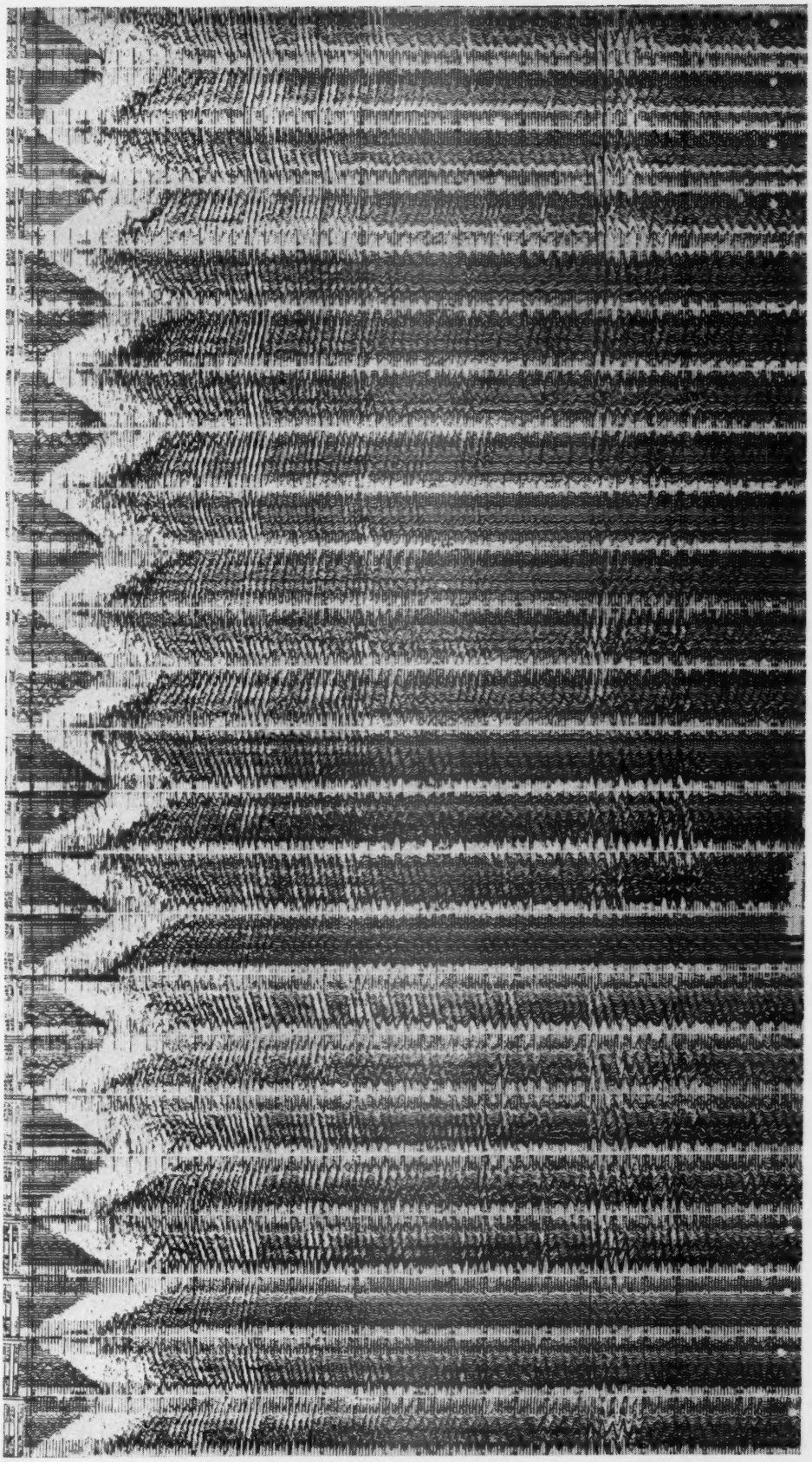

FIG. 4. A closed loop record section taken in Gaines County, western Texas.

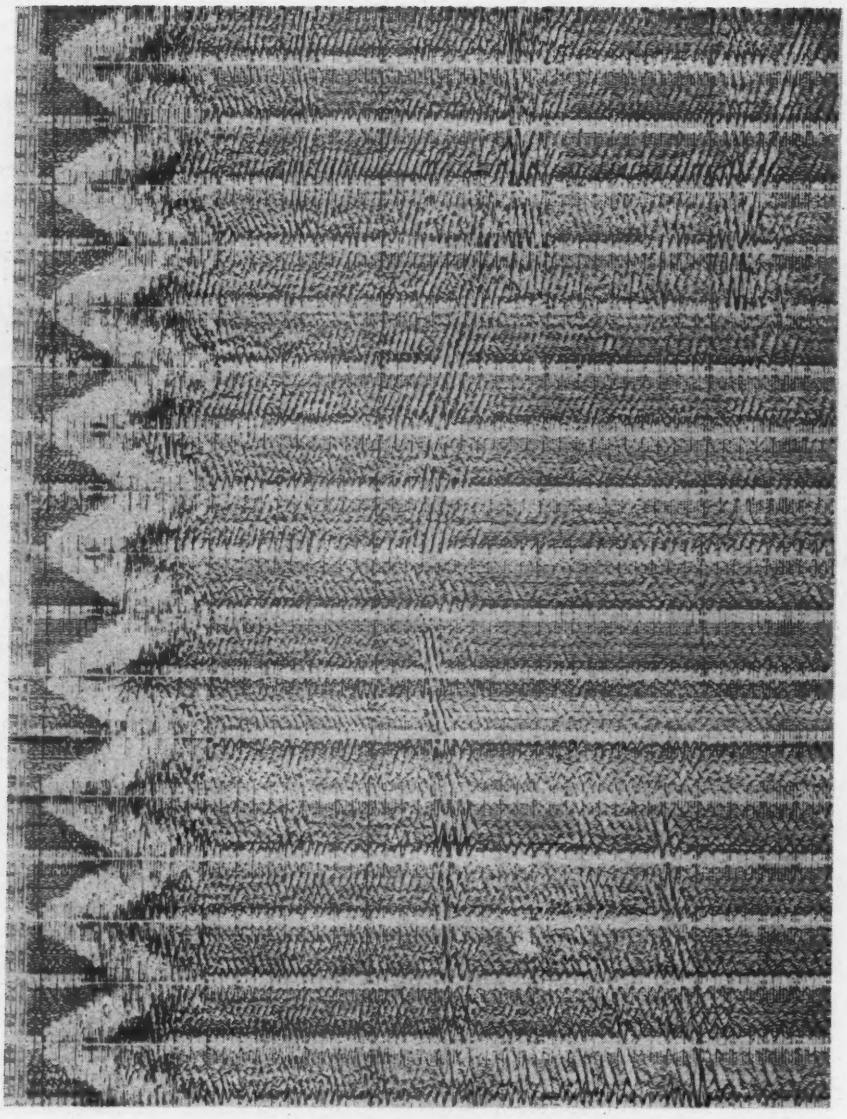

FIG. 5. A continuous straight line record section profile taken in Oklahoma showing a prominent anticline.

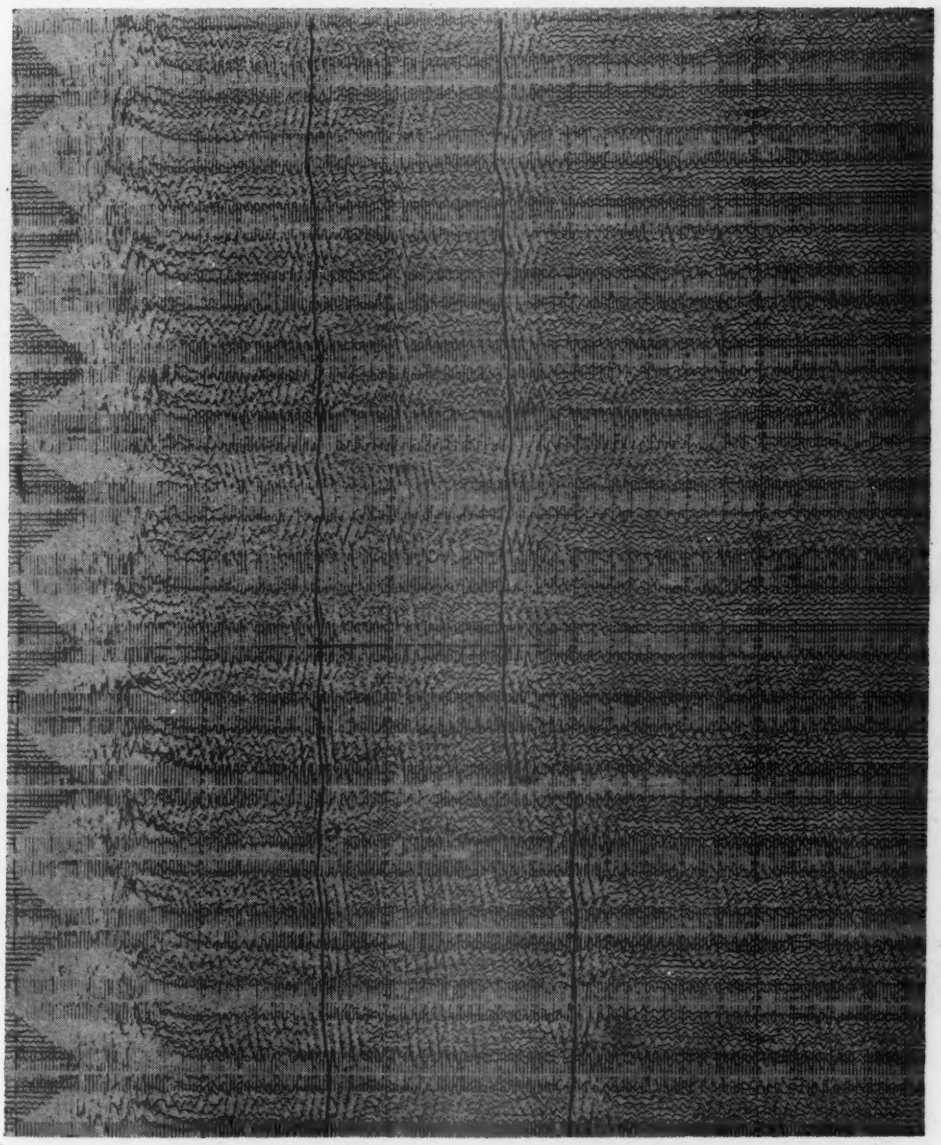

FIG. 6. A continuous straight line record section profile taken in Central Oklahoma showing a prominent fault in the Ordovician section not detectable in the Pennsylvanian section.

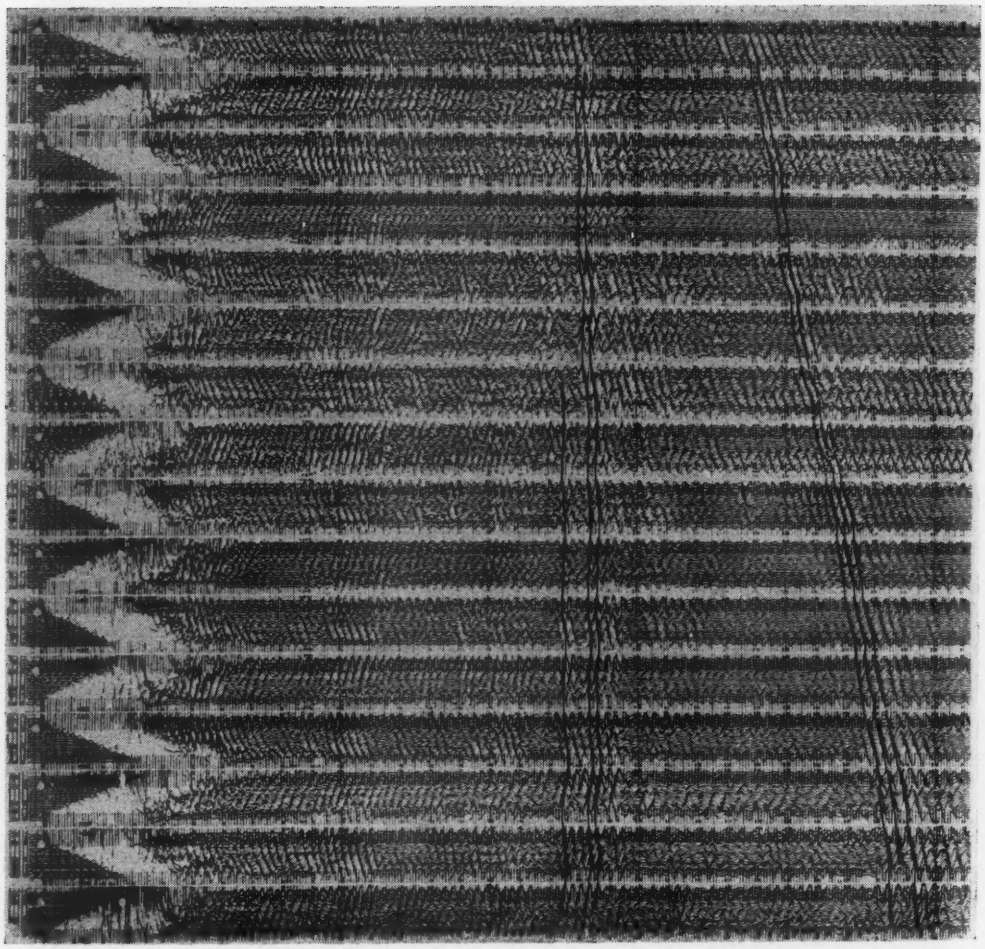

FIG. 7. A continuous straight line record section profile taken in southwestern Texas showing a prominent unconformity between the Frio and Vicksburg sections.

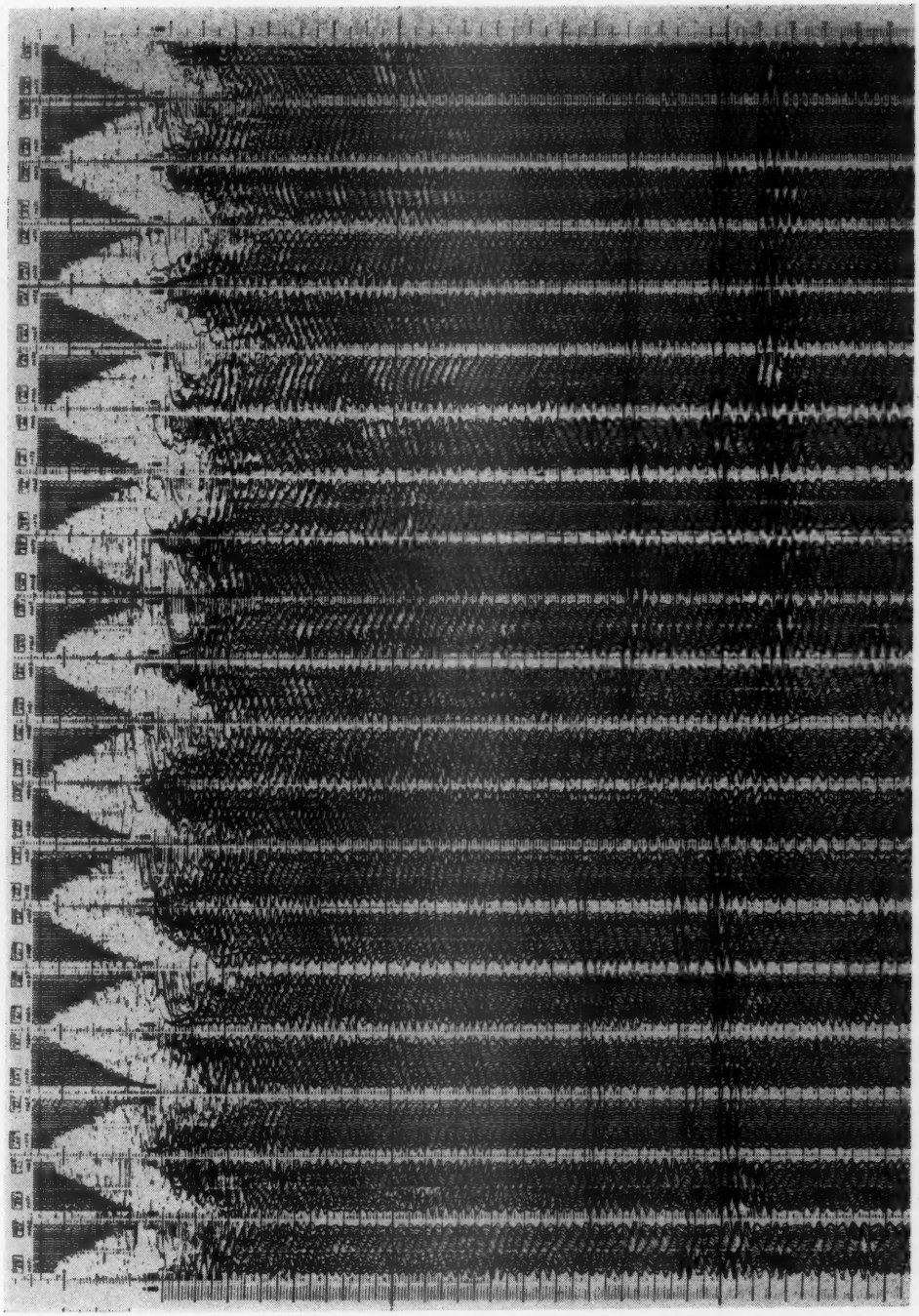

FIG. 8. A continuous straight line record section profile taken in southern Texas showing a fault in the Claiborne and Wilcox sections.

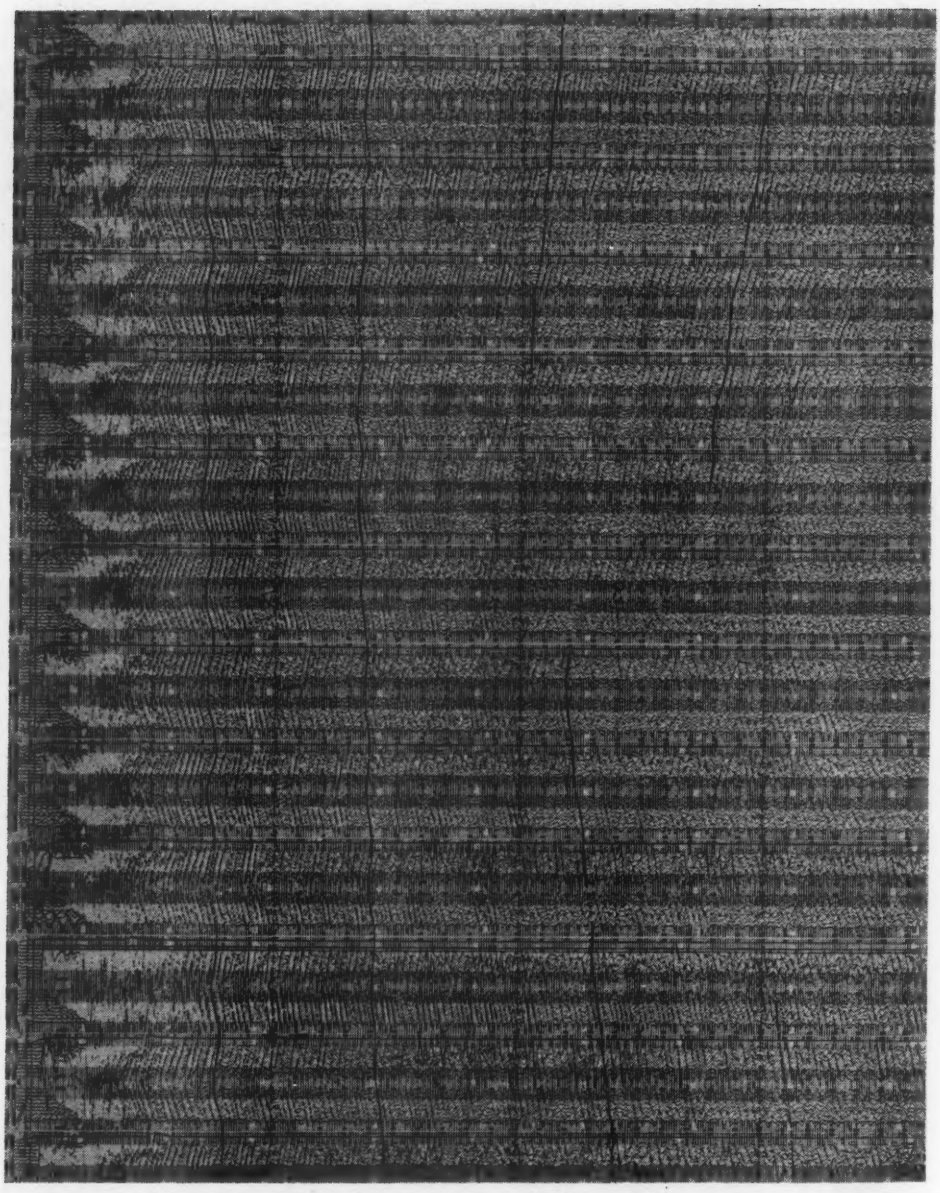

FIG. 9. A continuous straight line record section profile taken in about 100′ of water offshore Texas across a prominent structure shown in the Miocene section.

CONCLUSIONS

Probably the greatest single objection to record sections will come from those accustomed to use of records of conventional dimensions. Experience has generally shown that this objection disappears as an individual uses the sections. Where this objection persists, the double recording feature could be utilized to yield one conventional record and one suitable for record section assembly. The design and construction of a suitable constant-speed camera and inking devices are considered essential to the method and may be considered by some to be disadvantageous. Where records lack character and lateral continuity, the method may not clearly demonstrate advantages.

The record section, however, allows an interpreter to review a relatively large amount of data and to screen quickly seismic work to identify the critical places. It is a rather interesting experience to start with a record section and, by the simple procedure of marking a reflection arrival, have a value of time suitable for entry on maps. The record section allows both the interpreter and the administrative staff to secure quick comprehensive impressions of the features mapped. The designer of seismic equipment may rapidly screen a great many records for clues which are important in suggesting improvements. The field observer can more readily recognize the need of apparatus adjustment of various sorts by a glance at the record section than by seeing the separate records as they are processed. The repetition from record to record, on a composite section, of faulty apparatus adjustment becomes quite evident.

The confined dimensions of the record section allow use of lines at selected positions to be filed with final maps to augment the knowledge of the history of the structural development pictured on the separate maps where the maps at several levels may fail to give the complete story. Experience with their use for both current interpretation and subsequent review has shown the seismic record section to be a convenient and useful tool.

ACKNOWLEDGMENT

Appreciation is expressed to the Continental Oil Company for publication privilege.

NEUTRON LOGGING OF DRILL HOLES: THE NEUTRON-NEUTRON METHOD*

C. W. TITTLE,† HENRY FAUL,‡ AND CLARK GOODMAN§

ABSTRACT

Experiments were performed to determine the distribution of thermal neutrons and of indium resonance neutrons in continuous hydrogenous media and in pipes passing through hydrogenous media. Included in the study were water, brine, mixtures of sand and water, and mixtures of sand and brine. Experiments in a continuous typical barite drilling mud showed that the neutron distributions were essentially the same as in water. Also, from the point of view of these experiments, oil and fresh water are nearly identical.

These experiments show that well fluid (and, by inference, cement) imposes serious limitations on the sensitivity and accuracy of the neutron-neutron logging method. The indium resonance neutron response (or, in general, the intensity of epithermal neutrons) is a more reliable indicator of hydrogen content of the formation than is the thermal neutron response. The neutron-neutron method of chlorine determination was found to be not sensitive enough to be useful with brines of the concentrations ordinarily found in reservoirs.

INTRODUCTION

The present paper is concerned with the neutron-neutron or *n-n* method, in which the neutrons themselves are detected, after slowing down and diffusing in the formation and, in some instances, returning to the hole to be picked up by a neutron detector. The field use of this method has only recently been reported in the literature (Deegan, 1950), but no detailed information on the possible advantages of the method has been available. The response is similar to that of the neutron-gamma (or *n-γ*) method (Faul and Tittle, 1951). By virtue of the greater sensitivity of the *n-n* method to the ability of the formation to absorb slow neutrons, it is possible under certain favorable circumstances to distinguish brine from oil or fresh water. Both the *n-n* and *n-γ* methods detect hydrogen and hence can locate porous zones. Since porous formations are nearly always fluid laden, and since the fluids encountered are always hydrogenous (oil, water, brine, gas), the hydrogen log can be interpreted in terms of porosity (Bush and Mardock, 1950). Gypsum, which contains hydrogen in solid combination, might erroneously be interpreted as a porous formation. Gas might also be misinterpreted as petroleum or water in a less porous formation, if hydrogen content alone is employed as a measure of porosity. The methods discussed in the present paper in conjunction with the density log (Faul and Tittle, 1951), may lead to more quantitative determinations of porosity.

There is a serious limit to the ability of the *n-n* method to detect brine. We

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find that casing and well fluid are important factors. In most instances they obscure the picture to an extent that makes the method impracticable. Attention has been directed toward these fundamental limitations. Laboratory experiments designed to show what can and what cannot be done have been performed under controlled conditions. An attempt has been made to develop a quantitative method of interpretation.

Cement outside the casing, since it is hydrogenous (typically 55 percent water by volume), also imposes limitations and hinders interpretation, but a given thickness of cement would be equivalent to a somewhat smaller thickness of well fluid (typically 80 percent water or equivalent by volume). We have performed no experiments with cement, but the experiments on well fluid can be applied to problems involving cement by arguing in terms of equivalent thicknesses.

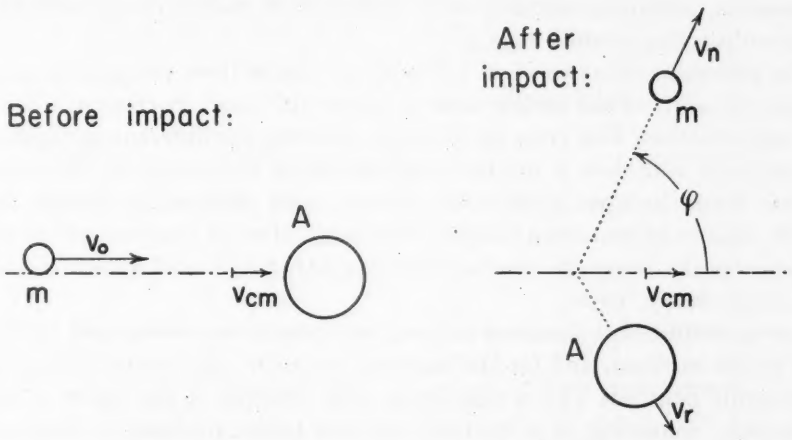

FIG. 1. Classical model of elastic neutron scattering; m=neutron mass, A=mass of struck nucleus, V_0=initial velocity of neutron, V_n=final velocity of neutron, V_r=recoil velocity of struck nucleus, ϕ=angle of scattering, V_{cm}=velocity of the center of mass.

GENERAL CONSIDERATIONS

Let us consider an essentially point source of neutrons surrounded by a mass of matter so large that only a negligible fraction of the neutrons can escape; i.e., in an effectively infinite medium. Let us further assume, for the time being, that the medium consists of a single chemical element of atomic mass A and atomic number Z.

Every neutron emitted by the source will then collide with the nuclei (collisions between neutrons and electrons can be disregarded) of the medium, and the collisions will be of three distinct types:

A. *Elastic Scattering* (*Figure 1*).—The neutron may strike the nucleus much like a marble hitting a billiard ball and rebound in such a way that the total momentum of the neutron and the nucleus is the same before and after the

collision. Some of the kinetic energy of the neutron will be lost to the nucleus (recoil energy), and the fractional amount will depend only upon the relative masses. The velocity and direction of the center of mass of the system remain constant throughout, and the entire process can be described in terms of elementary mechanics of elastic particles (Marshak *et al.*, 1947 and 1949).

B. *Inelastic Scattering.*—Instead of a simple mechanical collision, the neutron may impart a greater portion of its kinetic energy to the nucleus, leaving it in an excited state. The emitted neutron has considerably less energy than the incident neutron, and the excited nucleus returns to ground state usually by the emission of one or more gamma rays.

C. *Capture.*—In some cases, the impinging neutron forms a compound nucleus which either: (a) disintegrates by the emission of charged particles (protons, alphas, or fission fragments), (b) settles to a stable ground state by gamma ray emission (radiative capture), or (c) decays by β^- radioactivity (with or without accompanying gamma rays).

The probability that an atom will undergo any of these processes is generally expressed in units of the nuclear area (1 barn $= 10^{-24}$ cm^2) or cross section σ for a particular reaction. The cross sections are different for different isotopes of the same element and show a marked dependence on the energy of the impinging neutron. Some isotopes have large capture cross sections at certain neutron energies, known as resonance energies (Figure 2). Most of the pronounced capture resonance peaks occur at neutron energies between 1 and 50 ev (Goldsmith *et al.*, 1947; Adair, 1950).

Let us assume that the cross sections for inelastic scattering and capture are small in our medium, and for the moment, consider only elastic collisions. The source emits neutrons with a velocity v_0. The velocity of the center of mass of the system, consisting of a neutron and the target nucleus, is then $v_{cm} = mv_0/(m-A)$, assuming the nucleus to be stationary with respect to the source. But m is practically unity in atomic mass units, and we may write $v_{cm} = v_0/(1-A)$. If we place the origin of our co-ordinate system at the center of mass of the two particles, the velocities will be $v_0/(1-A)$ for the nucleus, and $Av_0/(1-A)$ for the neutron. In the center of mass system, the magnitudes of these velocities will remain the same before and after the collision, although the directions will change. (The following discussion is largely based on the lectures of E. Fermi, 1949.)

We may then compute the final velocity v_n of the neutron with respect to the source by adding the velocity vector of the center of mass to the velocity vector of the neutron in the center of mass system. It follows that

$$E = v_n^2/2 = v_0^2(A^2 - 2A\cos\theta - 1)/2(1 - A)^2 \qquad (1)$$

where E is the final energy of the neutron, θ is the angle of scattering in the center of mass system, and the neutron mass $m = 1$. The corresponding angle ϕ in the laboratory system (with respect to the source) is given by

$$\cos\phi = (A\cos\theta + 1)/(A^2 + 2A\cos\theta + 1)^{1/2} \qquad (2)$$

from which it can be shown that the average value

$$\overline{\cos \phi} = 2/3A \tag{3}$$

showing that the neutrons tend to be scattered in the forward direction. This forward scattering is greatest for collisions with the lightest nuclei (hydrogen, $A = 1$).

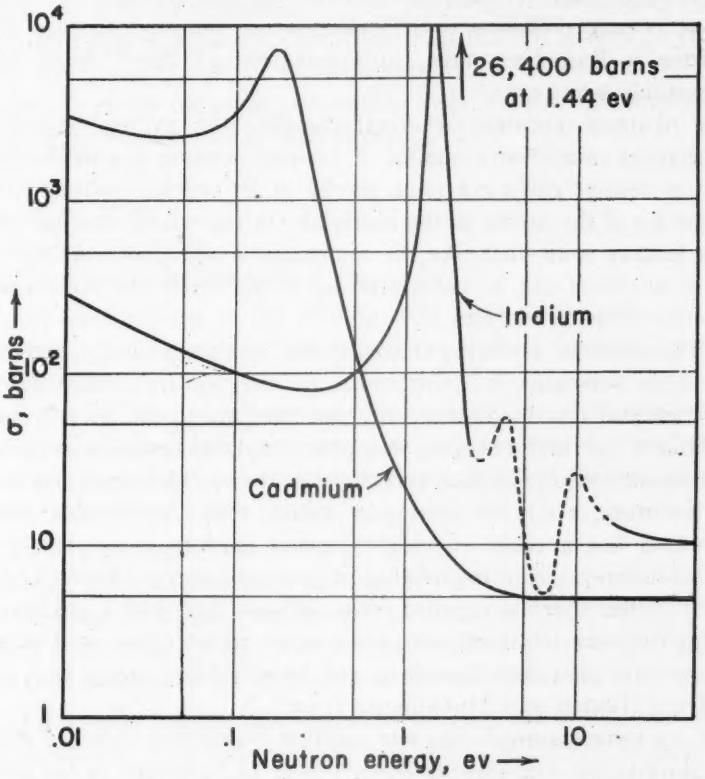

FIG. 2. Total neutron cross sections of indium and cadmium (after Goldsmith, Ibser, and Feld).

The neutron energy loss per collision can be computed from:

$$E_0/E = (A + 1)^2/(A^2 + 2A \cos \theta + 1) \tag{4}$$

which has the mean logarithmic value

$$\xi = \left[\ln \frac{E_0}{E}\right]_{av} = 1 - \frac{(A-1)^2}{2A} \ln \frac{A+1}{A-1}. \tag{5}$$

For hydrogen, the geometric mean energy $\overline{E}$ (Bethe, 1937) of the scattered neutron is given by

$$(\overline{E}/E_0)_H = 1/e$$

where e is the base of the Napierian logarithms (2.718 · · ·). Hence, it is seen that on the geometric average a neutron loses more than half its energy in a collision with a proton, but it loses only a very small fraction of its energy in an elastic collision with a nucleus of a heavy atom. Consequently, for a given number of collisions, *hydrogenous material is by far the most effective as a slowing-down medium for neutrons.* In addition, the elastic scattering cross section of hydrogen is fairly large: 21 barns for neutron energies between 1 ev and 10 Kev. Only about twenty collisions with hydrogen are required to slow the fastest neutron from a Ra-α-Be source (approximately 13 Mev) down to thermal energies (roughly 0.025 ev).

As the neutrons approach thermal energies, the average energy loss per collision becomes smaller and smaller. A thermal neutron in equilibrium with its surroundings neither gains nor loses energy in an average collision, due to the thermal motion of the atoms in the material. On the whole, thermal neutrons in a medium behave somewhat like the molecules of one gas in another, and the diffusion of neutrons can be calculated by using much the same reasoning as applies to the diffusion of gases.

While the neutrons are being slowed down, we can generally neglect capture, especially if the substance is hydrogenous, for the capture cross sections of most nuclei for fast and intermediate energy neutrons are small. As soon as the neutrons approach thermal energies, however, capture becomes important. The capture cross sections of common terrestrial elements (hydrogen, oxygen, carbon, silicon, aluminum, etc.) are relatively small, with the notable exception of chlorine which has a relatively high thermal capture cross section ($\sigma_c = 31.5$ barns). This difference is of importance in neutron logging. (Boron and cadmium have much higher thermal capture cross sections (710 and 2,410 barns, respectively), but they are relatively rare in common rocks. These and other capture cross section data are taken from Ross and Story (1949), except that of chlorine, which is from Hibdon and Muehlhause (1950).

So far, we have assumed that our medium consists of only one element, but we have shown that the slowing-down power of hydrogen is far greater than that of any other common element. Consequently, if we are dealing with a mixed medium containing an appreciable concentration of hydrogen, the heavier nuclei contribute very little to the actual slowing-down process although they do materially affect the spatial distribution of the neutrons through their scattering properties.

In the experiments described below, neutron distributions in continuous media were investigated, and the effect of holes on the neutron distributions was studied.

THE EXPERIMENTS

The experiments in the present work on the *n-n* log have employed a Ra-Be source. The source contained 1.03 grams of radium and was constructed by the

modern pressed pellet process. It was handled by a special electromagnet on a 10-foot pole.

The experiments have been of two general types, which might be called experiments in continuous media and pipe experiments, respectively. Since the scattered neutrons are detected in the *n-n* method, the spatial distributions of neutrons in continuous media and in the pipes running through continuous media were measured. The distributions of slow neutrons (thermal and epithermal), resulting from the slowing down and diffusion of the fast primary neutrons from the source, are generally of the greatest interest.

Experiments in the following continuous hydrogenous media were performed to aid the interpretation of the pipe experiments:

a. water
b. saturated brine
c. sand-water mixtures
d. a typical barite drilling mud.

The neutron distributions in the drilling mud were practically the same as in water, hence to avoid complications water was used in the pipe experiments to simulate well fluid.

Various sizes of iron pipe were used as casing. Aluminum pipe was used to simulate uncased holes, since aluminum has low neutron scattering and capture cross sections (1.43 and 0.22 barns respectively, for thermal neutrons). Specific items which were investigated include:

a. effect of more than one string of casing
b. masking effect of well fluid and casing
c. eccentricity of logging instrument position
d. effect of an empty hole, or of a long essentially "empty" logging instrument, in distending the neutron distribution axially.

The Slow Neutron Spatial Distributions: Thermal and Epithermal Neutrons.— In the experiments, slow neutrons of two different energy ranges have been detected and their spatial distributions determined: (a) thermal neutrons, or neutrons substantially in thermal equilibrium with the medium and characterized by a Maxwell-Boltzmann number-speed distribution law with a most probable speed corresponding to an energy kT, where k is Boltzmann's constant and T the absolute temperature of the medium, and (b) epithermal neutrons, or neutrons just above thermal energies and generally ranging from about 0.2 ev upward. The particular epithermal energy employed in the present work was 1.44 ev, the energy of the principal neutron resonance in indium.

The thermal neutron distribution depends on the temperature of the medium. Since subsurface formations commonly have elevated temperatures of the order of 150 or 200°F., temperature needs to be considered in applying the results of laboratory experiments, ordinarily performed at about 20°C. (68°F.), to subsurface conditions.

EXPERIMENTAL RESULTS

Details of experimental arrangements and correction of data appear in Appendices A and B, respectively. The cadmium correction factor for indium resonance neutrons and the Bothe correction factor for thermal neutrons have been applied to the data.

Experiments in continuous media.—Thermal and epithermal spatial neutron

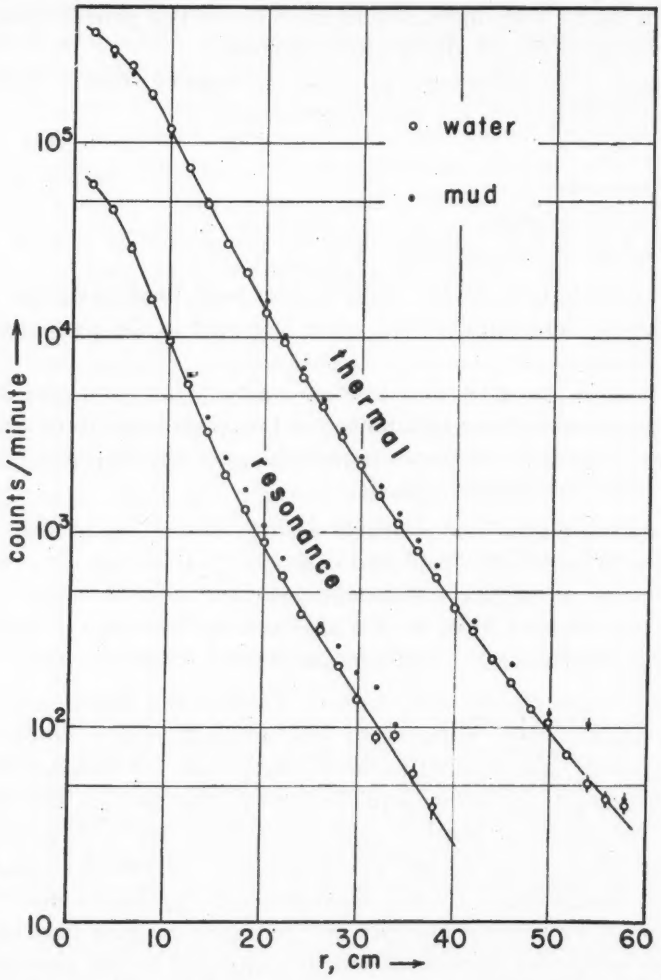

FIG. 3. Distribution of indium resonance and thermal neutrons around the Ra-Be source in water and in drilling mud (61.5 percent water, 35 percent barite, and 3.5 percent bentonite by weight, gravity 1.38). Note: Throughout this paper, neutron density is reported as the saturation counting rate of the front plus the back of a thin indium foil (see Appendix for details). The corresponding ordinates are marked "counts/minute." The distances from the source, plotted on the abscissae, are marked L when measured longitudinally along a pipe and r when measured radially outward through the material under study.

distributions in water, a typical barite drilling mud, a concentrated brine (NaCl solution), a mixture of sand and water, and a mixture of sand, water, and air are presented graphically in Figures 3–5. Details are given in the captions.

Figure 3 shows the distribution of indium resonance neutrons and thermal neutrons around the Ra-Be source in water and establishes that the neutron distributions in drilling mud and in water are nearly the same, i.e., water can be used to simulate well fluid. Figure 4 indicates that the indium resonance

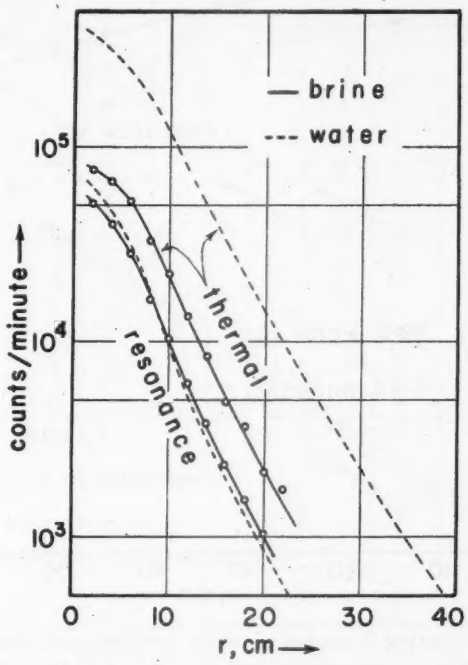

FIG. 4. Neutron distributions in concentrated brine (98 percent saturated NaCl solution). The distributions in water are shown for comparison (dashed lines).

neutron distributions in water and concentrated brine (98 percent saturated) are nearly the same, but there is a pronounced difference between the thermal distributions, principally due to the large thermal capture cross section of chlorine. As expected, Figure 5 shows that if the hydrogen concentration is reduced by the addition of sand to water, the neutron distributions fall off less rapidly, since hydrogen dominates in the slowing-down and diffusion processes. The effect is emphasized when most of the water is drained from the sand. This mixture represents the only instance in which the medium under study was not large enough to be considered effectively infinite in extent. The finite size tends to make the distributions fall off somewhat too rapidly at large distances from the source.

Experiments with pipes through water.—A number of experiments were made

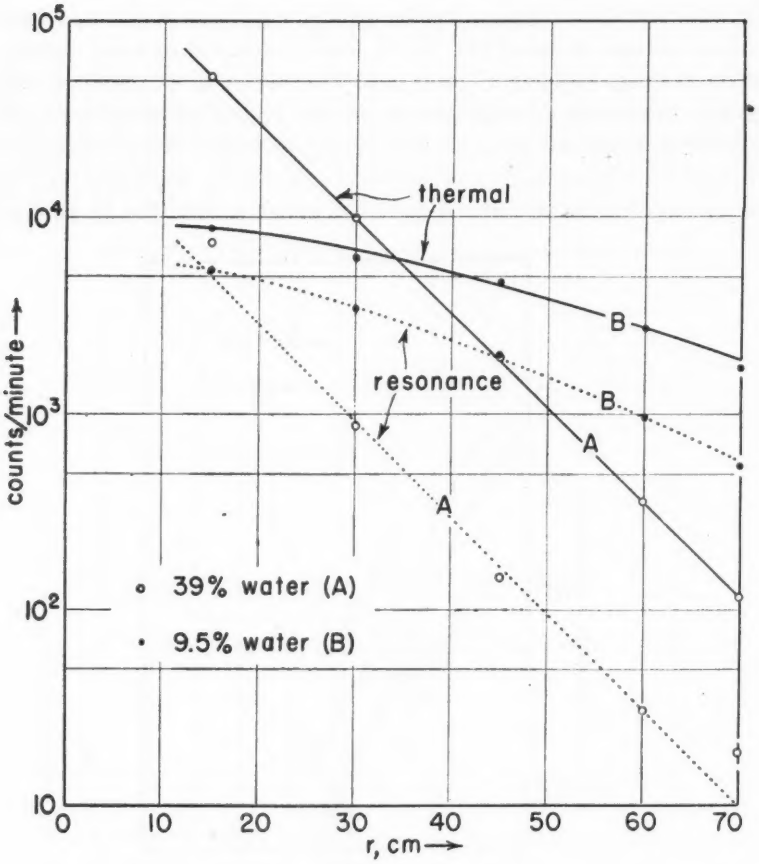

FIG. 5. Neutron distributions in sand of 39 percent porosity, saturated with water (A), and containing 9.5 percent water and 29.5 percent air by volume (B).

TABLE I

DIMENSIONS OF IRON AND ALUMINUM PIPES USED IN THE EXPERIMENTS

Nominal size (IPS)	Inside diameter	Wall thickness	Outside diameter
4-inch iron	4.03 in.	0.24 in.	4.50 in.
5-inch iron	5.05	0.26	5.56
— iron	5.50	0.25	6.00
6-inch iron	6.07	0.28	6.68
8-inch iron	7.98	0.32	8.63
4-inch aluminum	Same as 4-inch iron (used as instrument)		
6-inch aluminum	Same as 6-inch iron		

in pipes (iron and aluminum) of various dimensions summarized in Table I.

Figures 6–9 show the thermal and resonance neutron distributions along the axes of these pipes traversing water. Figure 6 indicates that the iron in the 4-inch pipe depresses the thermal neutron density as compared with the "uncased" hole, which is simulated by an aluminum pipe of the same size. Also shown is the effect of an additional 5-inch string of iron casing. The resonance distributions

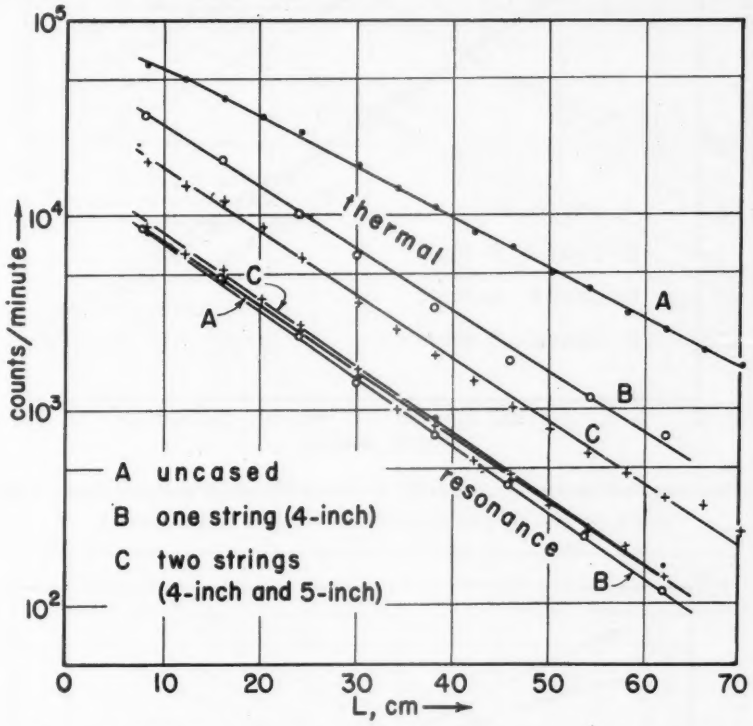

FIG. 6. Neutron distributions in cased and uncased holes through water. The uncased hole is simulated by a 4-inch aluminum pipe, which is practically transparent to neutrons.

were not affected very much by the presence of the iron. The space between the two pipes was filled with water. Figure 7 shows how the neutron distributions inside a 4-inch aluminum pipe, representing a logging instrument (outside diameter 4.5 inches), depend on the size of the casing. The space between casing and instrument was filled with water in each instance. Since the medium beyond the pipe was also water, it was anticipated that the effect of the iron would be the least for the largest pipe. Figure 8 shows how the neutron distributions in aluminum pipes through water depend on the pipe size. The neutron distributions in the larger hole fall off more slowly with distance. Figure 9 shows the same effect with iron pipes. The holes contained only the neutron source and detecting foils with their holders.

Experiments with pipes through concentrated brine.—Figures 10–14 present

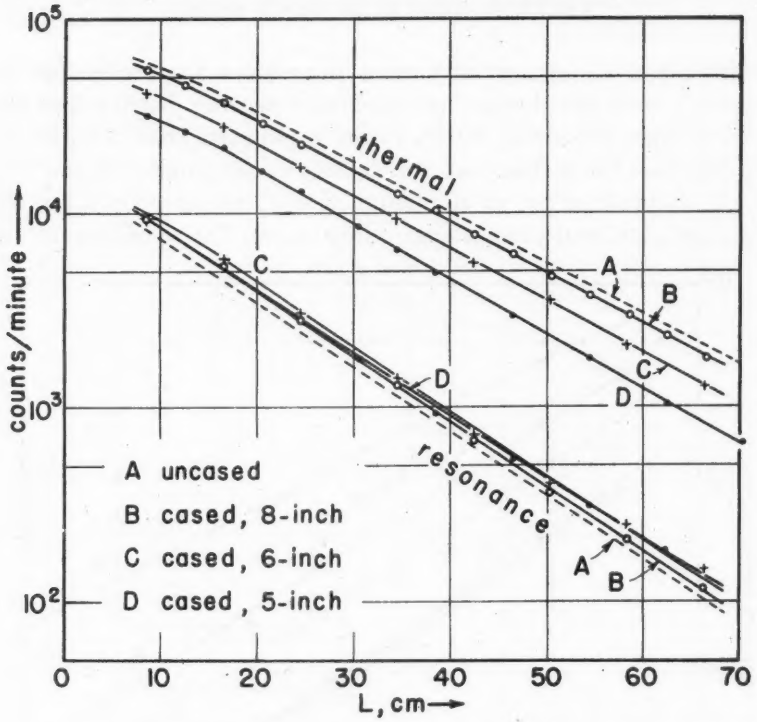

FIG. 7. Neutron distributions in cased holes of various diameters in water. Distributions in 4-inch uncased hole are shown by dashed lines for comparison.

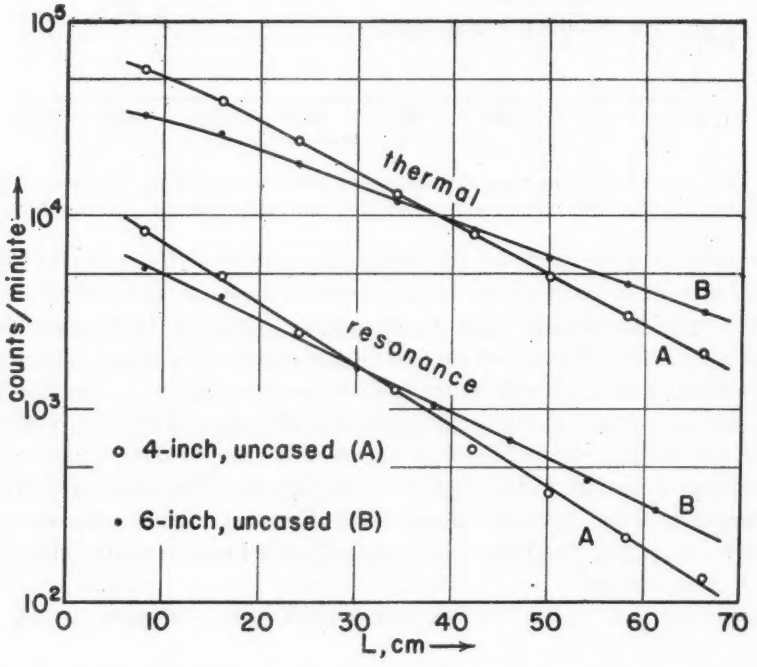

FIG. 8. Neutron distributions in uncased holes of two different diameters in water.

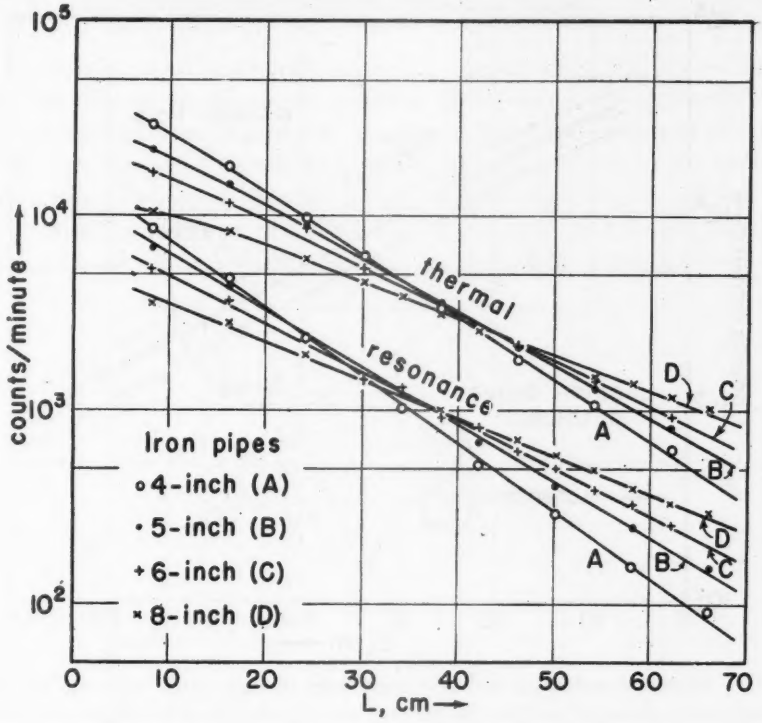

FIG. 9. Neutron distributions in essentially empty iron pipes of four different diameters in water.

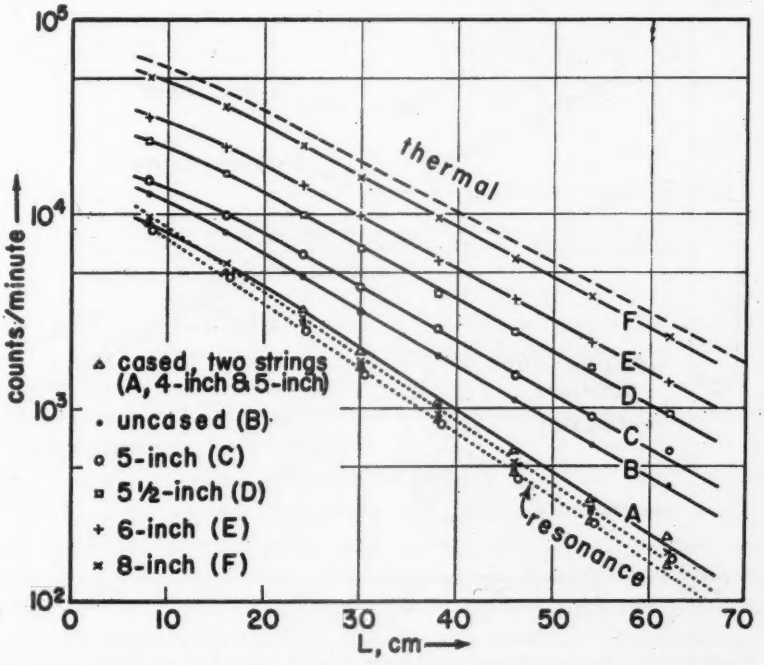

FIG. 10. Neutron distributions in cased and uncased holes through 98 percent saturated brine. The distribution in an uncased hole through water is shown for comparison (dashed line).

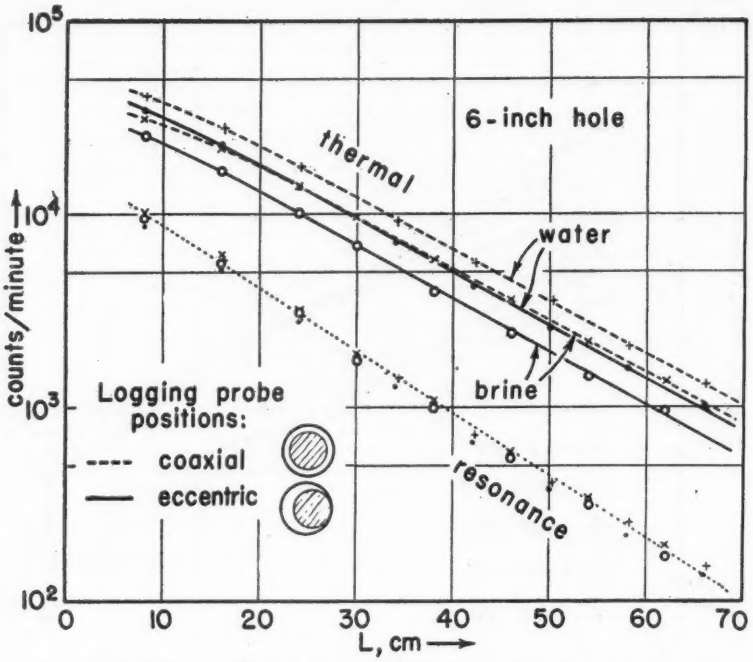

FIG. 11. Neutron distributions in 6-inch cased holes through water and saturated brine with logging instrument in coaxial position (dashed line) and extreme eccentric position (solid line). Well fluid is water.

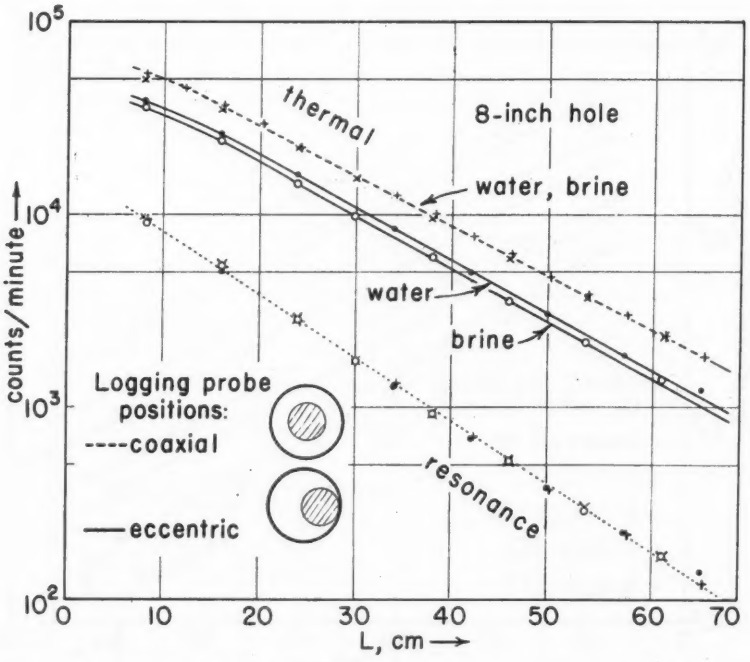

FIG. 12. Neutron distributions in 8-inch cased holes through water and saturated brine with logging instrument in coaxial position (dashed line) and extreme eccentric position (solid line).

results of various experiments with pipes in a 98 percent saturated sodium chloride solution. Figure 10 shows the neutron distributions along the axes of the pipes. The 4-inch aluminum pipe served as the logging instrument in all instances except the one marked "Cased, two strings (4 and 5 inches)," in which both pipes were iron. The space between pipes was filled with water, serving as well fluid. The masking effect of well fluid is clearly shown. The larger the layer of well fluid, the more nearly is the distribution like that of the uncased hole in

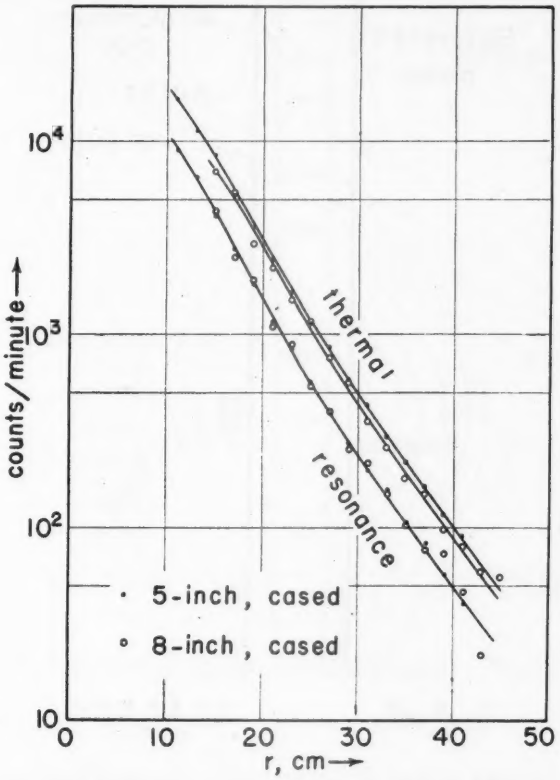

FIG. 13. Neutron distributions in saturated brine radially outward from cased holes. The neutron source is on the axis of the cased hole.

water. With the $1\frac{3}{4}$-inch layer of well fluid in the 8-inch cased hole, the well fluid alone is being logged.

Eccentricity of the logging instrument.—Figures 11 and 12 illustrate the effect of eccentricity of the logging instrument in 6-inch and 8-inch cased holes. Water served as well fluid between probe and casing; the medium beyond the casing was water or concentrated brine. The difference in thermal distributions in the instrument for water and concentrated brine beyond the casing was increased slightly by the eccentricity but not enough to be decisive. The masking effect of

well fluid is still severe. It is seen that variations in radial position of the instrument in the well will produce fluctuations in response, so that it is desirable to use a positioning device to hold the probe in either a coaxial or an eccentric position.

Radial neutron distributions around a well.—Figure 13 shows the neutron distributions radially outward into concentrated brine for 5-inch and 8-inch

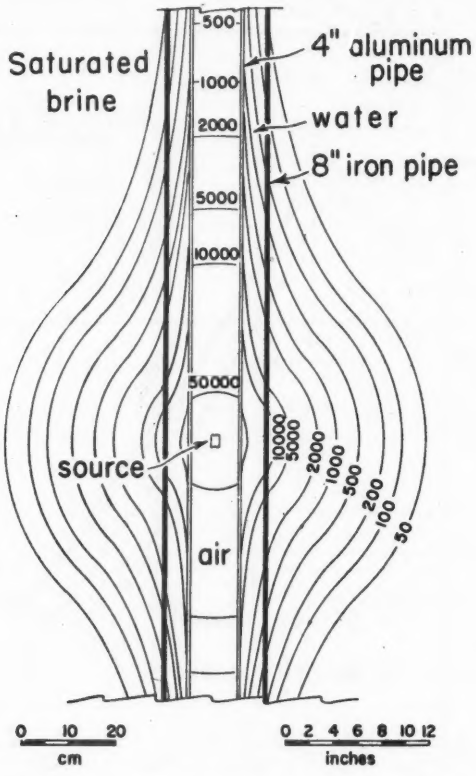

FIG. 14. Contours of equal thermal neutron flux in a cased 8-inch well through concentrated brine (idealized).

cased holes. The aluminum instrument was essentially empty, as in all the experiments involving it, and the space between instrument and iron pipe was again filled with water. There is little difference between the two conditions. Figure 14 is a sketch of contours of equal thermal neutron flux in and around the cased 8-inch well. The effect of the hollow inner pipe in stretching the neutron distribution is clearly shown. Since measurements were made only axially and radially, positions of the curves at intermediate points are only suggestive. Many more experiments of this type, in which the neutron distributions are measured around wells in various media of geological interest, will have to be

performed before a real understanding of the neutron logging processes is attained.

Experiments with pipes through brines of different concentrations.—Figure 15 shows the neutron distributions in uncased holes (lined with aluminum pipe 4.5 inches in outside diameter) through brines of various concentrations. Figure 16 reveals similar variations for 5-inch cased holes, in which water filled the

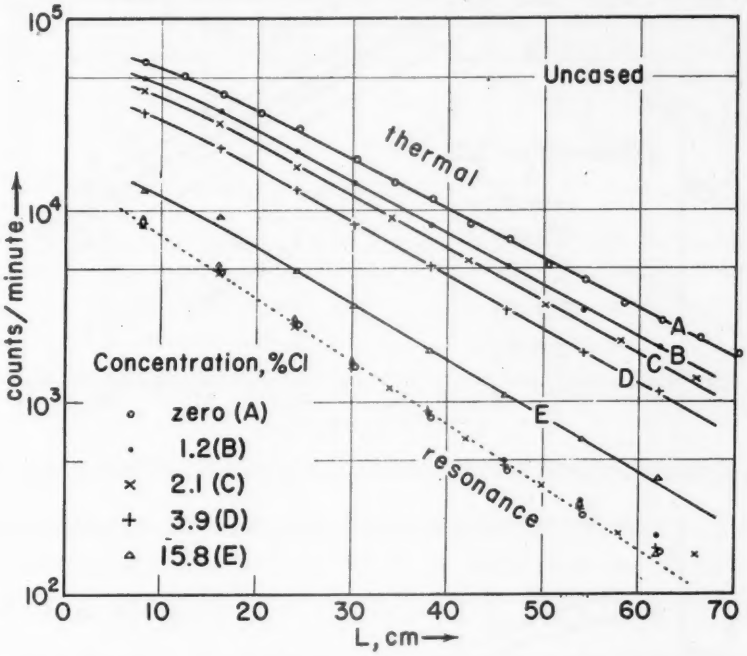

FIG. 15. Neutron distributions in an uncased hole through brines of different concentrations.

annular space between the 4.5-inch aluminum instrument and the 5-inch iron pipe.

Experiments with pipes through a mixture of sand and water.—The silica sand used in these experiments was obtained from the Ottawa Silica Co., Ottawa, Ill. The mixture obtained by pouring the sand into the experimental tank while spraying it with water had a pore space which was 39 percent of the total volume, considerably more porous than typical oil reservoirs (10–30 percent). Figure 17 shows the neutron distributions along the axes of empty 4-, 5-, and 8-inch iron pipes through the sand-water mixture. One of these experiments showed that introduction of the aluminum logging instrument pipe had a negligible effect on the neutron distributions. Figure 18 shows the axial neutron distributions in the 4.5-inch O.D. logging instrument with no casing and with 5-inch and 8-inch casing. In the last two instances water filled the space between instrument and casing.

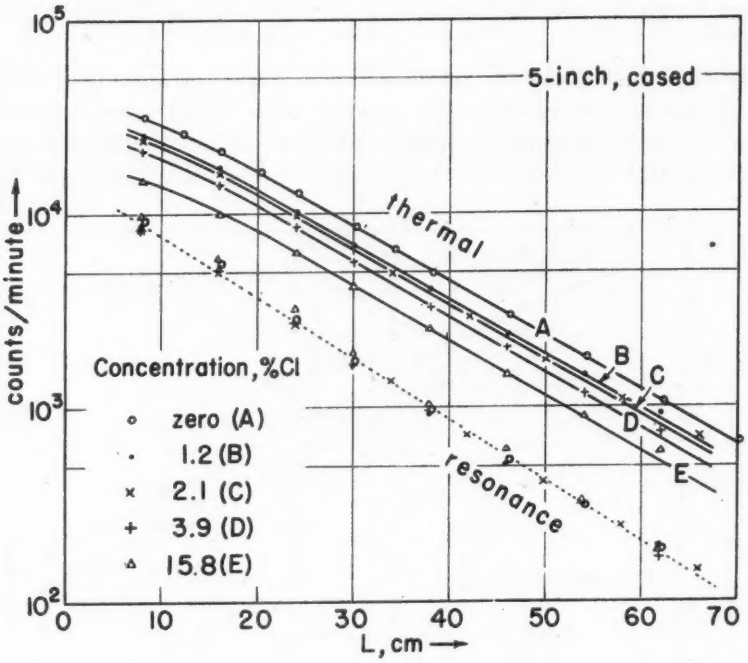

FIG. 16. Neutron distributions in a 5-inch cased hole through brines of different concentrations.

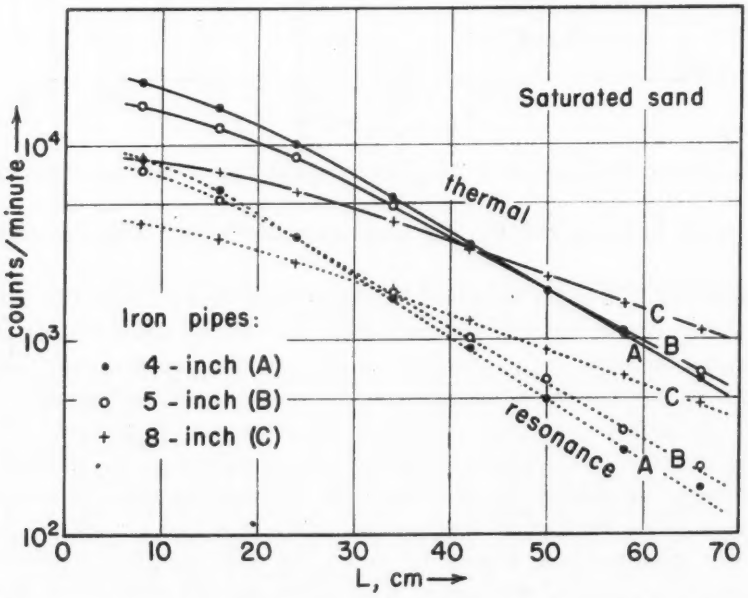

FIG. 17. Neutron distributions in empty 4-, 5-, and 8-inch pipes through a silica sand of 39 percent porosity saturated with water.

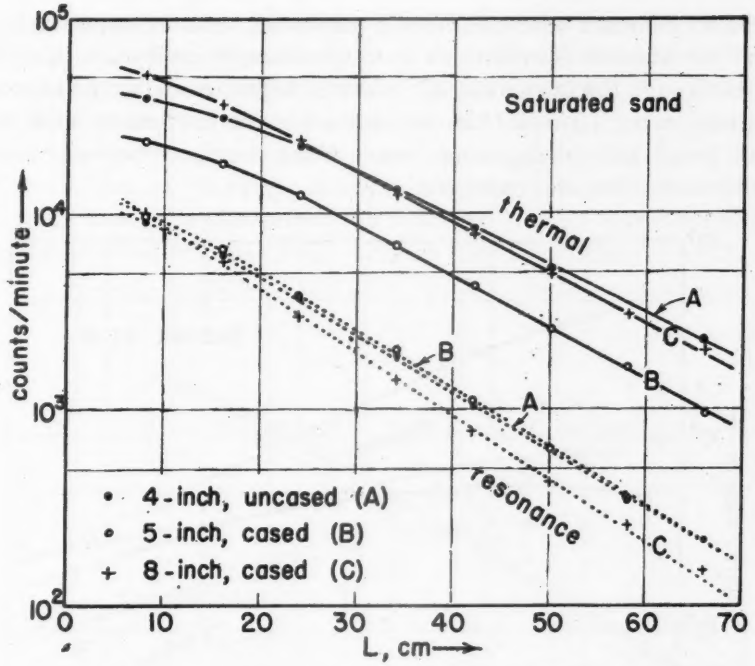

FIG. 18. Neutron distributions in cased and uncased holes in the saturated sand-water mixture.

Experiments with pipes through a mixture of sand, water and air.—The mixture was obtained merely by draining most of the water from the mixture of sand and water just described. The porosity was unchanged, i.e., 39 percent. The

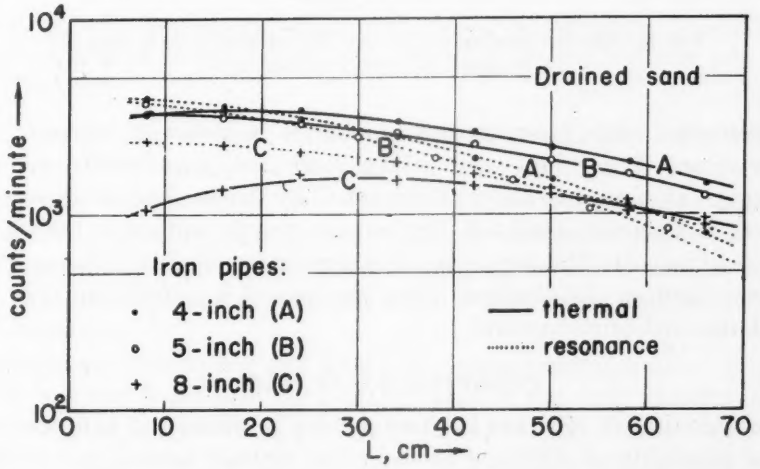

FIG. 19. Neutron distributions in empty 4-, 5-, and 8-inch iron pipes through a silica sand of 39 percent porosity containing 9.5 percent water and 29.5 percent air by volume (drained sand).

water and air contents were 9.5 and 29.5 percent by volume, respectively. Figure 19 shows the neutron distributions along the axes of empty 4-, 5-, and 8-inch iron pipes through the sand-water-air mixture. Figure 20 shows the axial neutron distributions in the 4.5-inch O.D. aluminum logging instrument with no casing and with 5-inch and 8-inch casing, water filling the space between instrument and casing in the last two instances.

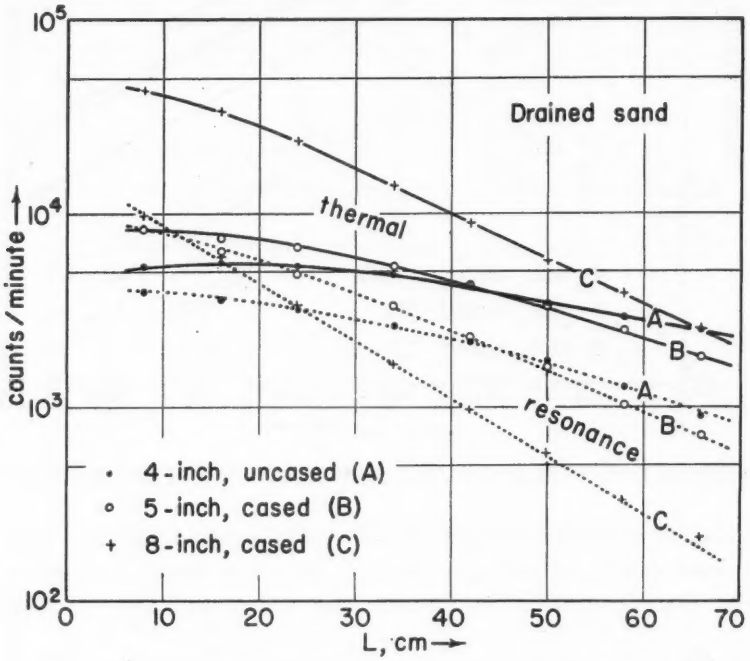

FIG. 20. Neutron distributions in cased and uncased holes through the sand-water-air mixture (drained sand).

Experiments with pipes through sand-brine mixtures of different chloride concentrations.—The brines used in the sand-brine experiments were dilute, containing 1.18, 2.32, 3.69 and 5.11 percent Cl by weight. The most concentrated brine was 31.5 percent saturated. The porosity was the same as in the sand-water mixture, 39 percent. The pore space was completely filled with brine. Figure 21 shows the neutron distributions along the axis of a 4-inch iron pipe passing through the sand-brine mixtures.

INTERPRETATION OF RESULTS

The quantitative relations between *n-n* log response and hydrogen content and the possibility of detecting brine by the thermal neutron *n-n* method are covered mostly by the data of Figures 15–21.

Neutron-neutron log response vs. hydrogen content of formation.—A strictly

functional relation between the *n-n* log response and the hydrogen content of the formation is not to be expected because of the influence of the non-hydrogenous components on the neutron distributions. This is especially true of the thermal neutron distribution, in which the macroscopic thermal capture cross section plays a strong part as illustrated by the data obtained with brine. Properties related to the rate at which the distributions (thermal or epithermal) decrease with distance along the pipe reflect the hydrogen content more accurately than the thermal neutron response itself, because the latter depends on the thermal

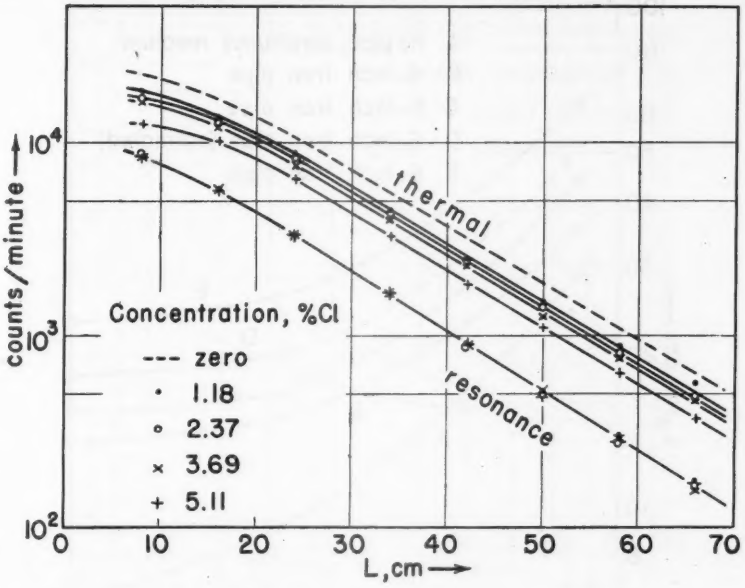

FIG. 21. Neutron distributions in empty 4-inch iron pipe through sand of 39 percent porosity saturated with brines of different concentrations. The brines contained 1.18, 2.32, 3.69, and 5.11 percent Cl by weight.

neutron density which in turn varies with capture cross section. The epithermal neutron response, however, is a fairly good indication of hydrogen content, since the epithermal neutron density depends on the neutron slowing-down properties of the medium and hydrogen tends to dominate the slowing-down process. Hydrogen content will be expressed as percent water by volume in the discussion to follow. Capture will in general be negligible at epithermal energies in cases of geological interest.

Equivalence of cement and well fluid.—A typical cement contains 55 percent water by volume. Some cements contain boron in the form of borax or boric acid which serves as a retarding agent, and due to the high capture cross section of boron (710 barns for thermal neutrons), such cements will be more effective in masking the formation. Roughly, 1.5 inches of boron-free cement are equivalent to 1.0 inch of well fluid.

Terminology.—Since aluminum is essentially transparent to neutrons, the holes produced by aluminum pipes will be referred to as uncased, with a diameter equal to the *outer* diameter of the pipe, whereas the iron pipes will always be designated by their *inner* diameter. In the following discussion, the terms "uncased," "cased," and "iron pipe" have the meanings described below.

Uncased: The aluminum pipe serves as logging probe with the formation in direct contact.

Cased: The $4\frac{1}{2}$-inch aluminum logging probe is located coaxially in an iron

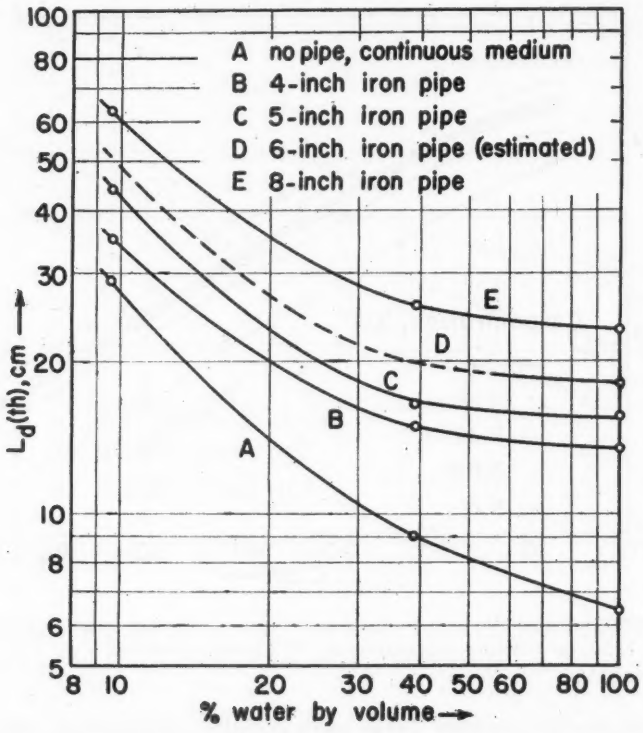

FIG. 22. Thermal decay length L_d (th) as a function of iron pipe size and percent water in formation (no well fluid).

casing of specified inner diameter (such as "5-inch cased"). In all instances where the term "cased" is used in the discussion, it is implied that well fluid is present in the space between probe and casing. Thicknesses of well fluid are as follows:

5-inch cased: $\frac{1}{4}$ inch
8-inch cased: $1\frac{3}{4}$ inch.

Iron Pipe: The term "iron pipe" will be used to designate holes lined with iron but containing no well fluid. These holes were essentially empty. Hole size designation means inner diameter of pipe.

Thermal decay length as a measure of hydrogen content.—The decay length

L_d(th) of the thermal neutron flux along the axis of the pipe, determining the rate at which the flux falls off in the Ce^{-L/L_d} representation of the distribution, is shown in Figure 22 as a function of iron pipe diameter and percent water in the formation. The decay length increases with increasing hole diameter and with decreasing hydrogen content of the formation. In the region of interest in oil production—10 to 30 percent water content, or the practical equivalent of 10 to 30 percent porosity whether filled with oil or water—L_d(th) is a fairly sensitive indicator of hydrogen content for a given hole size, but it should be noted

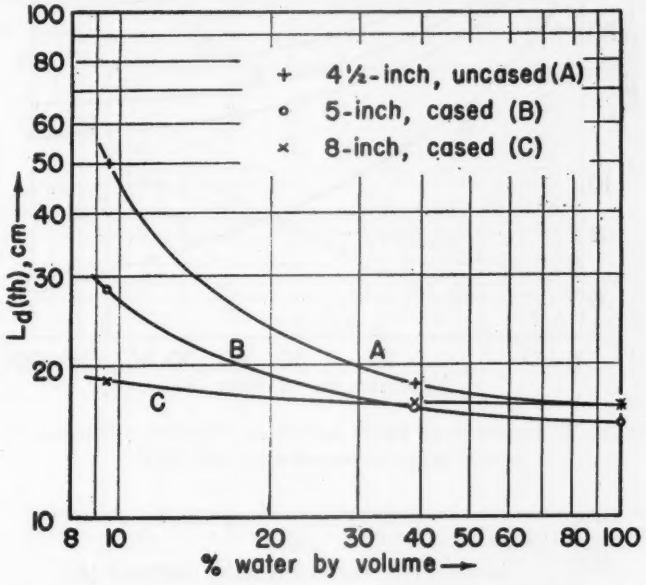

FIG. 23. Thermal decay length L_d (th) as a function of percent water in formation showing the effect of well fluid between probe and casing.

that conditions are comparatively ideal because of the absence of well fluid or cement. Figure 23 shows the effect of well fluid in reducing the sensitivity of the method. Even ¼-inch of well fluid in the 5-inch cased hole seriously affects the sensitivity, and 1¾ inches of well fluid masks the effect of the formation behind the casing. *The desirability of displacing as much of the well fluid as possible is thus demonstrated*, but in a cased hole with a fairly thick layer of cement beyond the casing—typically 1 to 2 inches—the method would be impractical for quantitative work.

Resonance (epithermal) decay length as a measure of hydrogen content.—Figures 24 and 25 show that there is little difference between the decay lengths of the thermal and resonance neutron distributions as measures of hydrogen content. The masking effect of well fluid is much the same. Another parameter which has the same significance as the decay length is the ratio of two detector readings at different distances from the source.

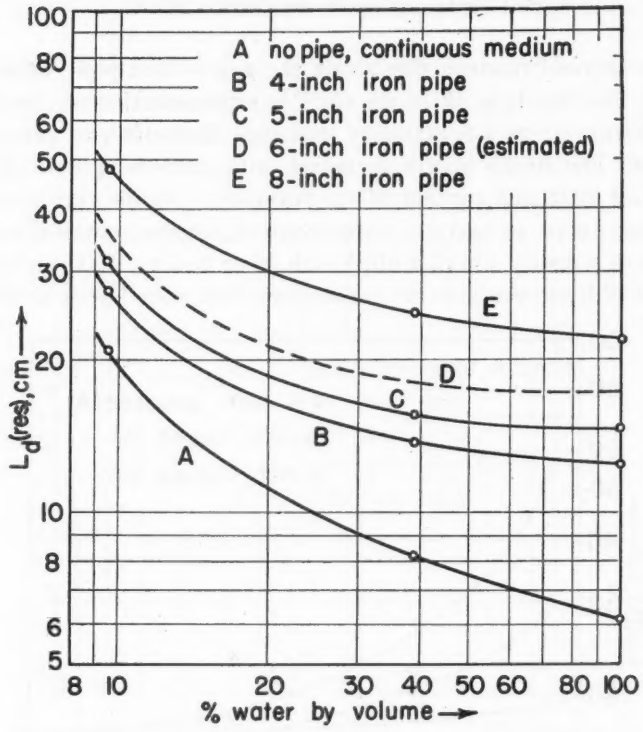

FIG. 24. Resonance decay length L_d (res) as a function of pipe size and percent water in formation (no well fluid).

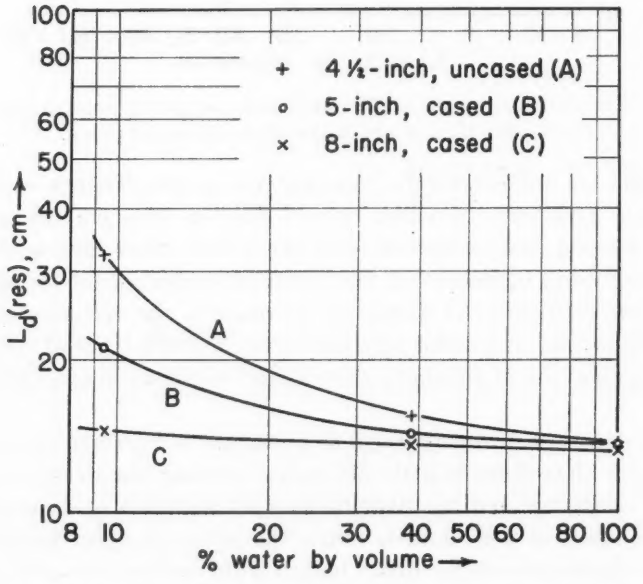

FIG. 25. Resonance decay length L_d (res) as a function of percent water in formation, showing effect of well fluid between probe and casing.

Resonance response as a measure of hydrogen content.—The response N_{res} of a long detector sensitive to the indium resonance neutrons and extending along the axis of the pipe at points 30 to 60 cm from the source was obtained by integrating the measured distribution over this range. The length and position of this equivalent detector were chosen arbitrarily for the purpose of discussion. In most instances the detector lies within the exponential part of the distribution. Figure 26 shows the resonance response of the long detector as a function of iron pipe diameter and percent water in the formation. The flattening of the curve for the 8-inch pipe is a result of the particular detector position chosen; at larger

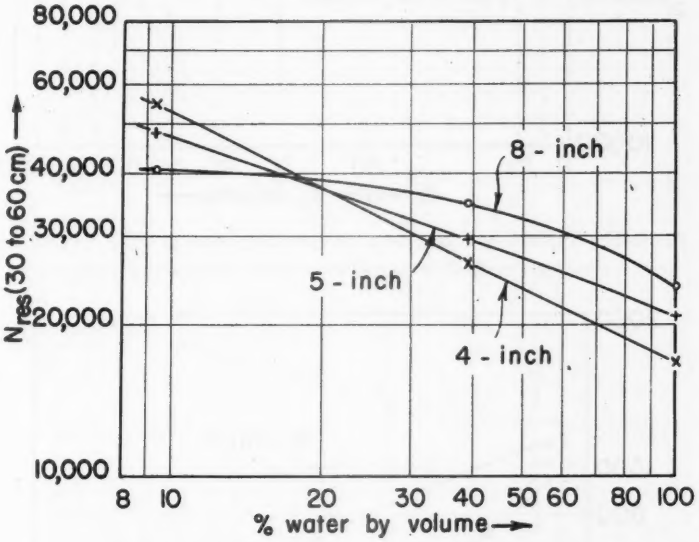

FIG. 26. Resonance response of a long detector extending from 30 to 60 cm from source, as a function of iron pipe size and percent water.

distances the effect would not be so pronounced. Figure 27 demonstrates the effect of well fluid on the sensitivity of the method. The $\frac{1}{4}$-inch layer of well fluid has little effect, as shown by the parallel curves for the $4\frac{1}{2}$-inch uncased and 5-inch cased holes. In the 8-inch cased hole the responses differ by 20 percent for 10 and 25 percent water content, a considerable improvement over the sensitivity of the decay-length method.

The effect of moving the resonance detector is illustrated by Figures 28 and 29, which represent the response of a point detector at 60 cm from the source. Sensitivity, as indicated by the slope of the curves, is increased, and the flattening of the curve for the 8-inch iron pipe is almost eliminated. Thus with proper detector positioning, the response of the resonance detector would be a fairly reliable indication of hydrogen content of the formation.

Ratio of responses of thermal and resonance detectors.—Figures 30 and 31

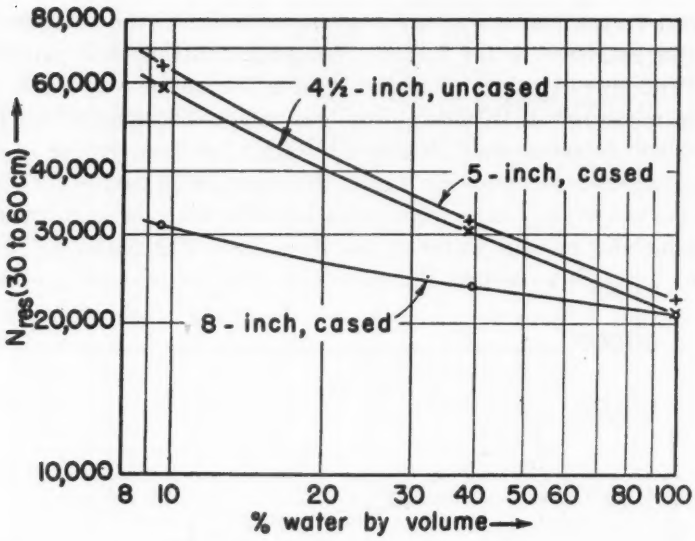

FIG. 27. Resonance response of a long detector extending from 30 to 60 cm from the source, showing the effect of well fluid between probe and casing.

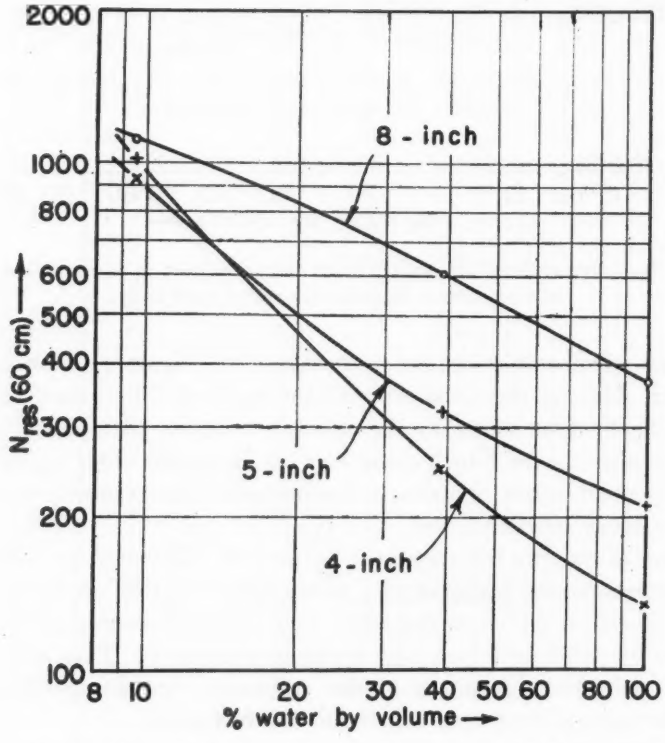

FIG. 28. Resonance activities at 60 cm from the source, as a function of pipe size and percent water.

show the ratio R of the response of a long thermal detector and that of a long resonance detector at the same location, extending 30 to 60 cm from the source. Since the resonance response is a measure of the hydrogen content and the number of thermal neutrons in the hole depends inversely on the ability of the formation to capture thermal neutrons, R is a measure of capture probability. The curves of Figures 30 and 31 are for chlorine-free formations. Any medium

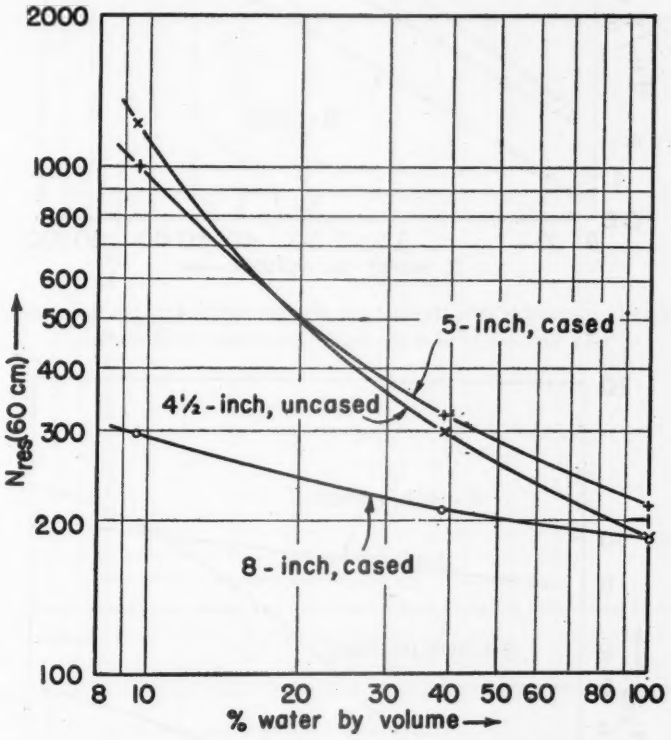

FIG. 29. Resonance activities at 60 cm from the source, as a function of percent water, showing the effect of well fluid between probe and casing.

in which a strongly absorbing element (such as chlorine) occurs will be characterized by a smaller thermal to resonance response ratio, and R can therefore be used as a parameter that indicates the chlorine content of the formation, on the assumption that other strong absorbers are absent. Figure 31 indicates a pronounced dependence of the parameter R on well fluid which will seriously limit the practicality of the method, as discussed below.

Chlorine determination by the n-n method.—Figure 32 shows how the parameter R depends on chlorine content of the brine in a sand formation of 39 percent porosity. The hole was lined with iron but contained no well fluid. R is a fairly sensitive function of chlorine content. However, in this case the porosity

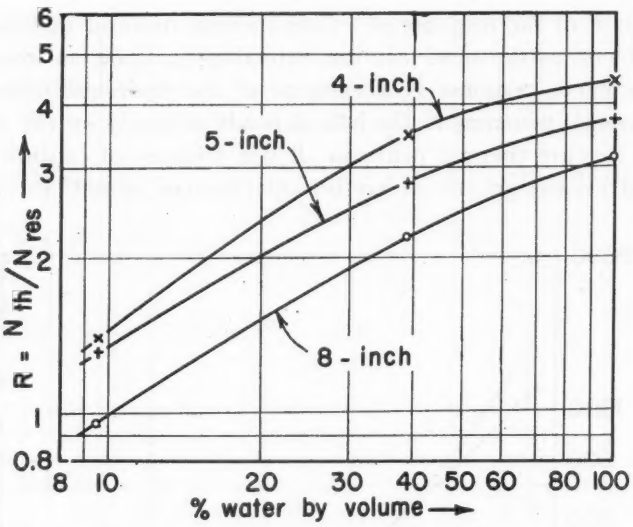

FIG. 30. Ratio of responses of long thermal and resonance detectors (30 to 60 cm from source) as a function of pipe size and percent water in formation.

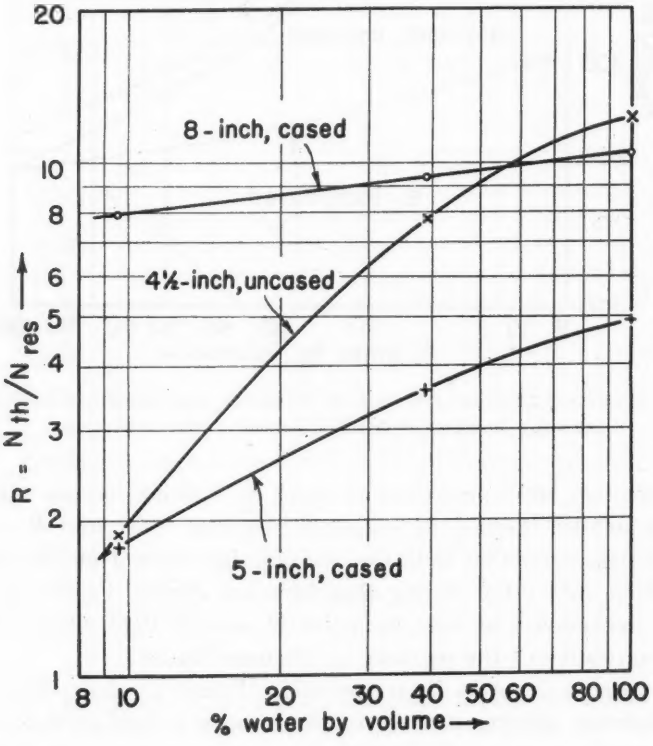

FIG. 31. Ratio of responses of long thermal and resonance detectors (30 to 60 cm from source) as a function of percent water, showing the effect of well fluid between probe and casing.

is higher than normal and the absence of well fluid or cement makes the prospects somewhat optimistic. Figure 33 is a compilation of all the data obtained in the present series of experiments concerning the possibility of detecting brine. The ratio of parameters R(water)/R(brine) is plotted as a function of percent Cl in the brine for various conditions. Enough data were taken to allow estimation of

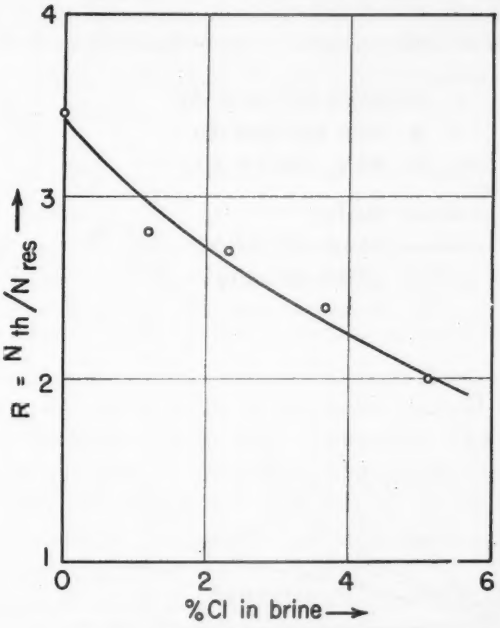

FIG. 32. Ratio of thermal to resonance response of long detector, extending from 30 to 60 cm from the source, in an air-filled 4-inch iron pipe surrounded by a sand-brine mixture, as a function of percent chloride by weight in the brine. Formation porosity is 39 percent of total volume. Pore space is filled with brine. The most concentrated brine shown is 31.5 percent saturated NaCl solution.

the curve for a 5-inch cased hole through a sand and brine mixture of 39 percent porosity. For a 5 percent brine, R(water)/R(brine) = 1.3. Since this still represents rather idealistic conditions—only $\frac{1}{4}$ inch of well fluid, no cement, brine considerably more concentrated than average, porosity twice as high as typical—it can be concluded that under field conditions the *n-n* method will not be a satisfactory procedure for determining chlorine content of the formation. Even in uncased holes, the layer of well fluid and the uncertainty of the hole size in most instances would impose severe restrictions on the method.

FIELD APPLICATIONS

Thermal and epithermal neutron detectors.—The method of thermal and epithermal neutron detection used in these experiments is obviously not suitable for field application. Equivalent results can be obtained by use of a proportional

counter containing boron, for example the gas BF_3, preferably with boron enriched in the isotope B^{10}. Normally such a counter would be sensitive to neutrons of all energies down to and including thermal energies but its sensitivity would be greatest at thermal energies, and ordinarily the density of the thermal neutrons is greater than that of the higher energy neutrons. Hence the response of the counter would primarily depend on the thermal neutron distribution. If

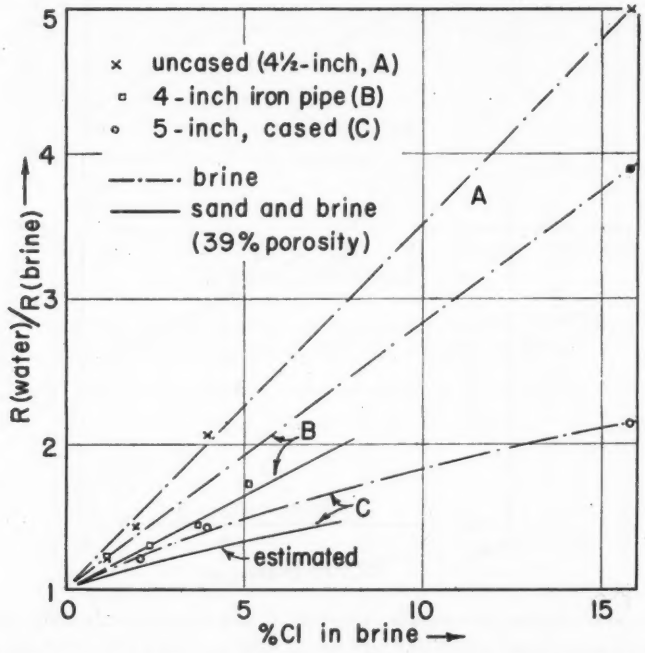

FIG. 33. Effect of casing and well fluid on ability of the *n-n* log to detect brine. Ratio of N_{th}/N_{res} ratios as a function of percent chloride in brine in cased and uncased holes.

the counter is shielded by a layer of cadmium at least 0.02 inch thick, the thermal neutrons will be absorbed and will not reach its sensitive volume. The response will then be largely a function of the epithermal neutron density. Sensitivity will be rather low, but this can be compensated by use of a more intense neutron source. These considerations are intended to show only that practical detectors of the type needed in the *n-n* method can be devised; many arrangements are possible.

Field limitations.—It has been shown that the thermal neutron response depends critically on well fluid (and on cement). It would therefore be a poor indicator of hydrogen content of the formation. Furthermore, absorbing elements such as chlorine would tend to produce complications. The effect of well fluid, casing, cement, and neutron absorption can be reduced by detecting epithermal neutrons instead, and the epithermal neutron-neutron logging method should

therefore be a satisfactory indicator of hydrogen content. By virtue of the adverse influence of well fluid, casing, cement, and variations in hole diameter, the thermal-epithermal method of chlorine detection is faced with too many limitations to be practical in the field.

Comparison of n-n and n-γ logging methods.—A previous paper of this series (Faul and Tittle, 1951) is concerned with the neutron-gamma logging method. It is appropriate to say here by way of summary that the methods are of comparable sensitivity if epithermal neutrons are detected in the *n-n* method, but more work will have to be done to determine which method is the more accurate indicator of hydrogen content.

APPENDIX A: EXPERIMENTAL ARRANGEMENTS

The cadmium difference technique with indium metal foils was employed to determine the thermal and indium resonance neutron densities as a function of position. After an exposure of known duration, the indium was removed and its β-radioactivity (half-life of 54 minutes) measured by a thin-window Geiger-Mueller counter.

Figure 34 illustrates a typical setup of Ra-Be neutron source, foil holders, pipes, and media in the experiments. It represents a cased hole with well fluid between the aluminum logging probe and the iron pipe. The holder had a funnel at the top for ease in inserting the source. The indium detecting foils were placed in aluminum or cadmium holders for the thermal + resonance or resonance determinations, respectively. The holders were mounted on an aluminum channel with slots at fixed intervals relative to the source.

The pipes were about 4 feet long. The arrangement was centered in a cubical 4-foot tank containing the material representing the formation under study. In the experiments with low hydrogen content the media were not extensive enough to be considered as effectively infinite. In such cases, and especially in the case of nonhydrogenous media, the amount of material required in neutron diffusion experiments is vast.

The indium foils were circular discs 3 cm in diameter and approximately 0.003 inch thick. The average surface density was about 58 mg/cm^2. The foils were intercalibrated for both thermal and resonance neutron sensitivity. A set of some 20 foils is required for work of this type. The foils were first placed in the holders and the channel assembly inserted in the inner pipe. The source was then inserted for a timed interval—usually 54 minutes. The exposure was terminated by removing the source. After a delay of 3 minutes to allow for handling and to let the 13-second indium activity decay to negligible proportions, the most distant foil was counted on an end-window Geiger-Mueller counter shielded with lead. The other foils were counted in sequence. Each foil was counted both with its front and its back facing the counter window, and after correction for background count and for decay of the activity while waiting and counting, the activities of front and back were added to obtain a measure of the neutron

density (Amaldi and Fermi, 1937). An automatic continuous timing device was used to establish a rigid counting schedule. It was found desirable to store the indium foils in a cadmium box surrounded by paraffin to prevent stray activation. For the experiments in continuous media the same source and foil holders were used.

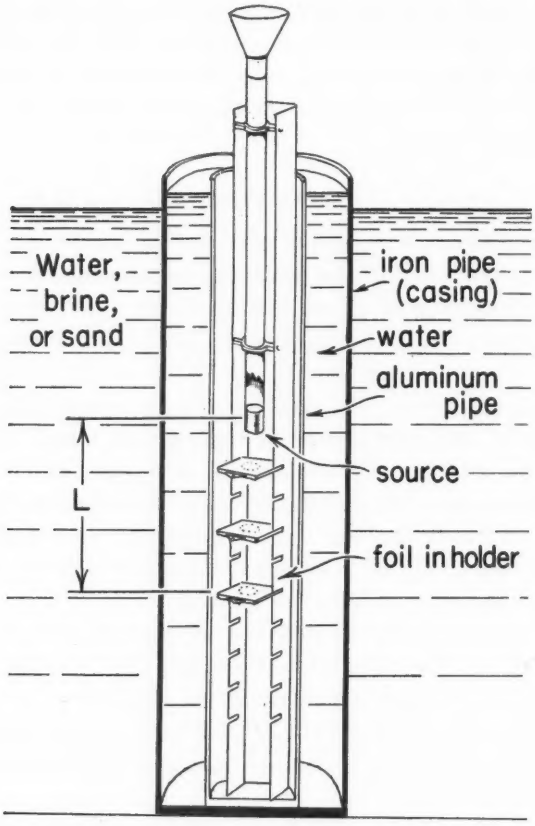

FIG. 34. Arrangement of pipes, foil, and source in some of the experiments (not to scale).

APPENDIX B: CORRECTIONS APPLIED TO INDIUM ACTIVATION DATA

For accurate work it is necessary to apply two corrections to the data: (a) cadmium is not perfectly transparent to neutrons of indium resonance energy (1.44 ev), so that for foils of the thickness used in these experiments (58 mg/cm^2), and for a cadmium thickness of 0.040 inch, it is necessary to multiply the measured resonance activity by a factor 1.13 (Kunstadter, 1950); and (b) the introduction of a thermal neutron detector depresses the thermal neutron density because it is necessarily a neutron absorber and acts as a sink for the diffusing neutrons (Bothe, 1943). The essential criterion is the probability that the same neutron may cross the foil more than once in its zigzag path through the medium. The

foil may thus "cast a shadow" upon itself by absorbing neutrons which otherwise would have returned to it. These corrections are discussed in detail by Tittle (1951).

The thermal neutron depression ("self-shading") correction factor F was nearly 1.0 for foils placed along the axis of the pipes in experiments, because the innermost pipe was always empty and had a large radius compared to the radius of the foil. However, the correction is necessary and was applied where the neutron intensity was measured radially outward into the medium and the foils were surrounded by the material under study. The different correction factors are shown in Table II. The effect is negligible for indium resonance neutrons in hydrogenous media.

TABLE II

SELF-SHADING (Bothe's *Selbstbeschattung*) THERMAL NEUTRON DEPRESSION CORRECTION FACTORS FOR VARIOUS MEDIA

Medium	Correction Factor F
Water	1.11
Drilling mud, gravity 1.38 (61.5 percent H_2O by wt)	1.10
Brine, saturated	1.06
Sand, water-saturated (39 percent porosity)	1.05
Sand, drained (39 percent porosity, 9.5 percent water by vol)	1.02

ACKNOWLEDGMENTS

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This work was carried on at the Massachusetts Institute of Technology (1946–1949) and supported in part by the Bureau of Ships and the Office of Naval Research. Our appreciation is also due the Gulf Oil Corporation for aid to one of us (CWT) in the form of the Gulf Oil Corporation Fellowship in Physics at the Massachusetts Institute of Technology. The Texas Company furnished a high-sensitivity gamma counter which served as background monitor in the experiments. The Baroid Sales Division of the National Lead Company and the Magnet Cove Barium Corporation contributed ingredients for the drilling mud.

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THE INVESTIGATION OF EARTH RESISTIVITIES IN THE VICINITY OF A DIAMOND DRILL HOLE*

A. R. CLARK[1] AND D. J. SALT[2]

ABSTRACT

The method of electrical images has been used to derive an expression for the difference in potential between two points close to a good conducting sphere in a poor conducting medium. The results indicate that the presence of a conducting ore body of commercial size near a drill hole can be detected by suitable electrical measurements made in the hole.

The results of a test of the method in a drill hole near a small conducting sulphide ore body are given.

INTRODUCTION

Geoelectrical investigations, in which the detection of buried conductors depends on the distortion by the conductor of a given potential configuration applied at the surface, must be confined to relatively shallow depths. A diamond drill hole in an area offers an opportunity to greatly increase the depth which may be reached (1).

If a current electrode C_1 is placed in a drill hole in a homogeneous isotropic medium and four other current electrodes C_2 are placed on the surface symmetrically spaced around the collar of the hole at large distances from the hole, and the resistance to earth of each current electrode made the same, then C_1 will be a point of electrical symmetry as well as space symmetry. The vertical line through the point source C_1 will also be a line of symmetry with respect to the surface electrodes. If the material is not homogeneous the vertical line is no longer a line of symmetry and when current is sent from the central point electrode to the surface electrodes in turn, the difference in the drop in potential between any two points in the original line of symmetry provides a measure of the comparative conductivities of the materials in any of the four directions from the bottom of the hole. Thus a lowered potential measurement when the current flow is in a given direction indicates material of greater conductivity in that direction.

DISTORTION OF EQUIPOTENTIAL SURFACES BY A CONDUCTING SPHERE

A rigorous mathematical treatment of the problem encounters severe difficulties in attempting to apply the boundary conditions which must be satisfied at the rock-ore and rock-air interface even for bodies of very simple shapes. However, when the ore bodies are at large distances from the surface, the current

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flow near the body will not be appreciably affected by the boundary conditions at the air interface, and an approximation of the magnitude of the potential differences may be obtained by assuming the body to be a spherical conductor embedded in an infinite homogeneous medium, by regarding the current electrodes as small spheres, and by using the method of electrical images. In such a method the electrodes C_1 and C_2 (Figure 1) are replaced by charges of magnitude $\pm\rho_1 I/4\pi$ where ρ_1 is the resistivity of the medium in which the electrodes

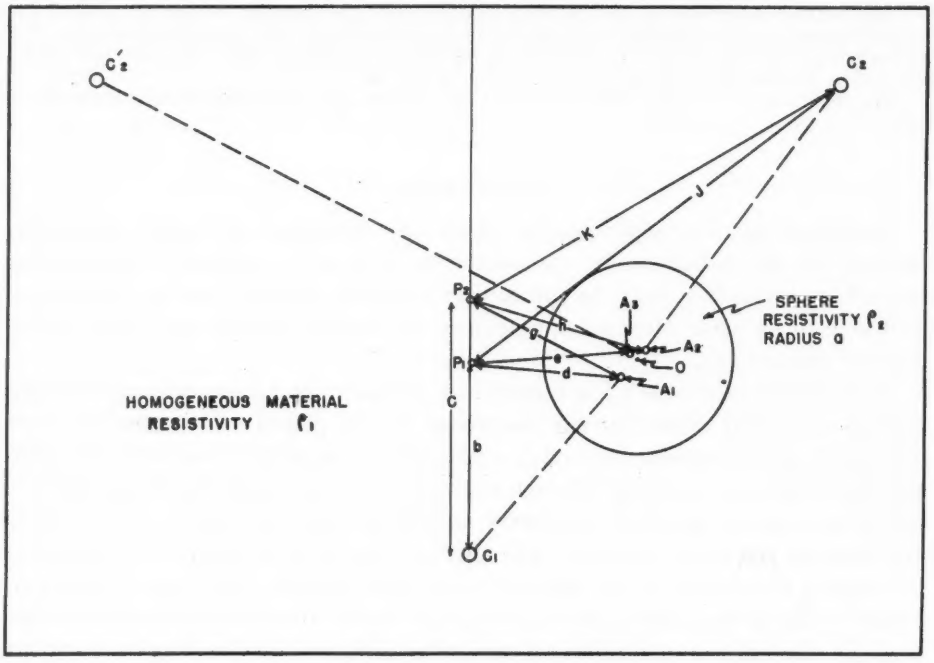

FIG. 1. Electrical images in a conducting sphere.

are situated and I is the current flow between C_1 and C_2. The charges at C_1 and C_2 induce charges on the conducting sphere whose effect at points external to the sphere is equivalent to point charges or "images" at A_1 and A_2, the distance of A_1 and A_2 from the center of the sphere along lines joining O and C_1, C_2, where a = radius of sphere, being a_2/OC_1 and a_2/OC_2 respectively (2). By the use of the condition that the current flow across the boundary between sphere and surrounding medium is a continuous function, the magnitude of images A_1 and A_2 may be shown to be

$$-\frac{\rho_1 I}{4\pi}\,\frac{a}{OC_1}\left[\frac{\rho_1-\rho_2}{\rho_1+\rho_2\dfrac{OC_1}{a}}\right] \quad \text{and} \quad \frac{\rho_1 I}{4\pi}\,\frac{a}{OC_2}\left[\frac{\rho_1-\rho_2}{\rho_1+\rho_2\dfrac{OC_2}{a}}\right]$$

where ρ_2 is the resistivity of the sphere. For a good conducting sphere in a poorly conducting medium ρ_2 is negligible compared to ρ_1 and the magnitude of the images becomes

$$-\frac{\rho_1 I}{4\pi}\frac{a}{OC_1} \quad \text{and} \quad \frac{\rho_1 I}{4\pi}\frac{a}{OC_2}.$$

The potential at any point P outside the sphere will be the sum of the potentials due to the two objects at C_1C_2 and the images A_1 and A_2. If, as an added simplifi-

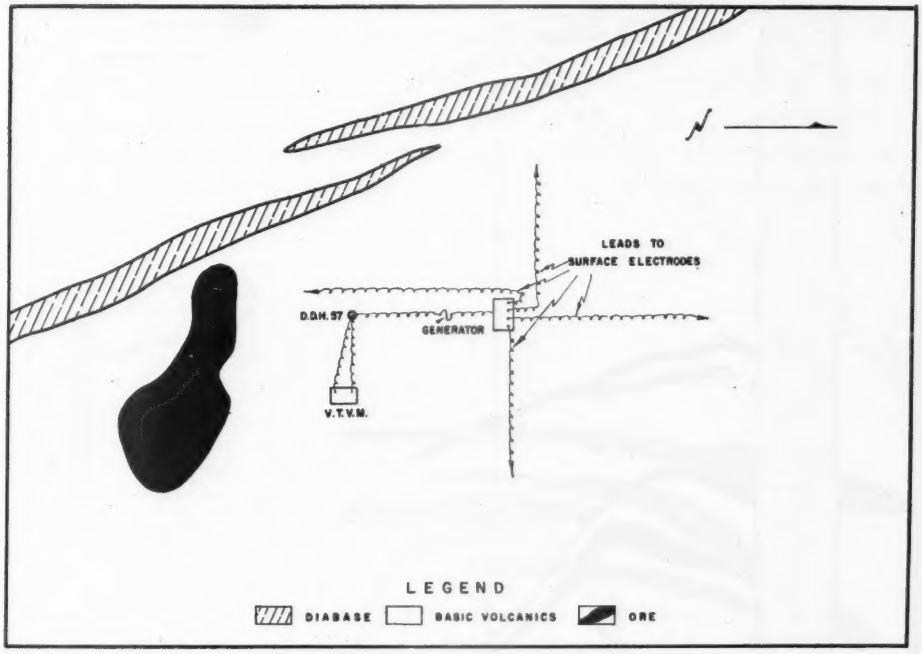

FIG. 2. Electrical set-up at Drill Hole 57.

cation, the center of the sphere and all electrodes be in the same plane the difference in potential between any two such points P_1 and P_2 will be given by ΔV where

$$\Delta V = \frac{\rho_1 I}{4\pi}\left[\left(\frac{1}{b}-\frac{1}{c}\right)-\frac{a}{f_1}\left(\frac{1}{d}-\frac{1}{g}\right)+\frac{a}{f_2}\left(\frac{1}{c}-\frac{1}{h}\right)-\left(\frac{1}{f}-\frac{1}{k}\right)\right]$$

where $f_1=OC_1$, $f_2=OC_2$ and the other letters represent distances as shown in Figure 1.

If C_2' is used as a current electrode, then the image A_2 must be replaced by image A_3, and the potential, $\Delta\overline{V}$, between P_1P_2 will be greater than ΔV since A' is nearer the potential electrodes than A_2. When the size of the sphere and its

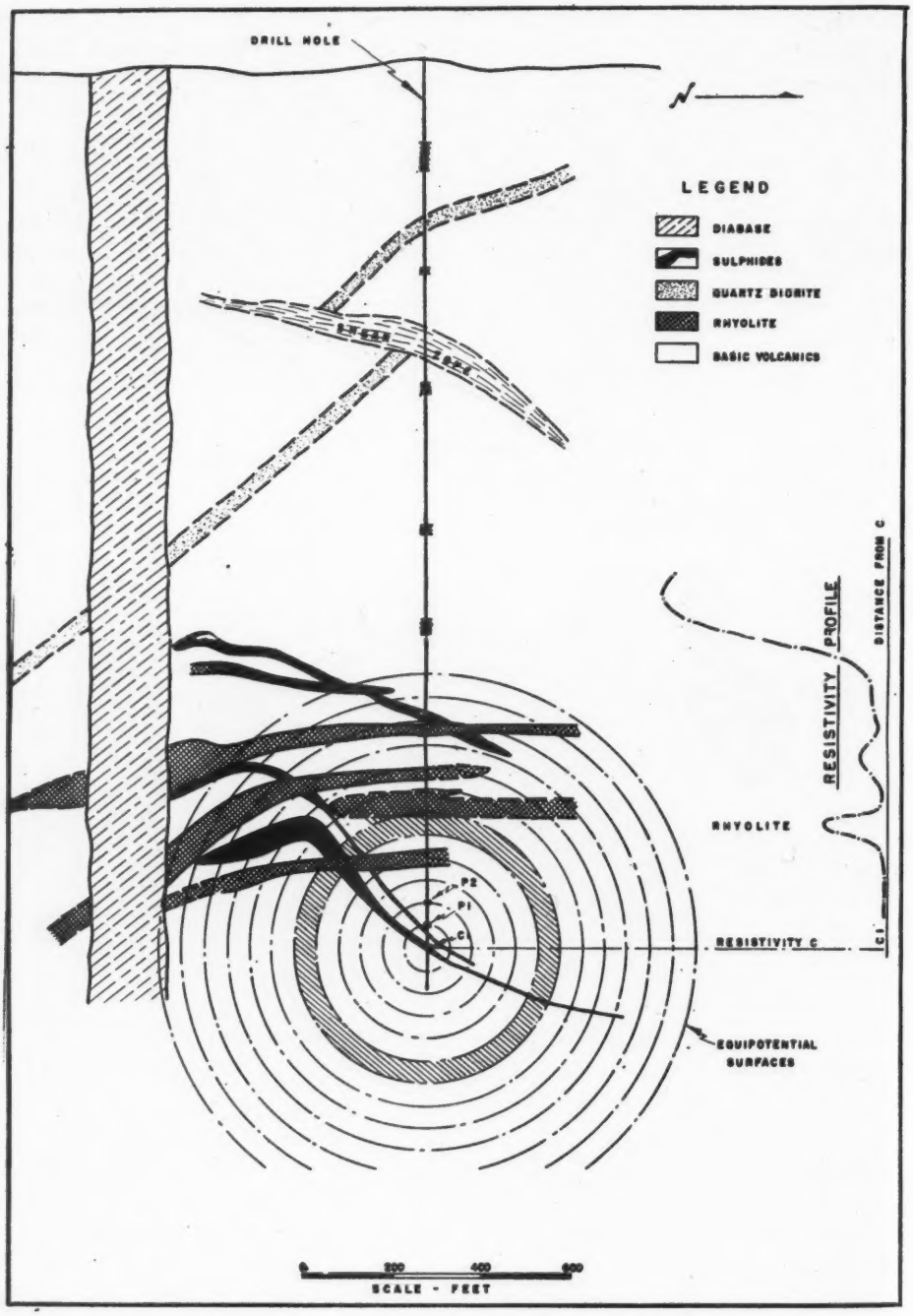

FIG. 3. Vertical N-S geological cross section through Drill Hole 57.

position relative to the electrodes is known a value of the ratio $\Delta\overline{V}/\Delta V$ may be obtained. For a conducting sphere of radius 100 feet, whose center is 150 feet both horizontally and vertically from C_1, and where C_2 and C_2' are 500 feet above and 1,000 feet horizontally from C_1, and where P_1P_2 are respectively 100 and 200 feet above C_1, the ratio is 1.04. Since a sulphide ore body of this radius would contain approximately one half million tons the effects produced by bodies of commercial size would be small but easily detected. The magnitude of the calculated results further emphasizes the necessity of making the resistance to earth of the surface electrodes exactly the same.

FIELD TEST OF THE METHOD

During the summer of 1949 the authors had the opportunity of testing the method on the property of the Lake Dufault Mines Limited, where the size and shape of a small sulphide ore body were accurately known from extensive diamond drilling. The relation of the test hole and the ore body is shown in plan and section in Figures 2 and 3.

TABLE I

Distance P_2 to collar	$\Delta\overline{V}$(North) ÷ ΔV(South)	$\Delta\overline{V}$(West) ÷ ΔV(East)
1,250 feet	1.03	1.02
1,300 feet	1.02	1.10
1,350 feet	1.05	1.37
1,400 feet	1.21	1.05
1,450 feet	1.20	1.23
1,500 feet	1.04	1.02
1,550 feet	1.08	0.79
1,600 feet	1.09	1.02
1,650 feet	1.01	1.01
1,700 feet	1.04	1.04
1,750 feet	1.14	1.10
1,800 feet	1.02	1.02
1,850 feet	0.94	1.00

Current electrodes were placed on surface 2,000 feet north, south, east, and west of the collar of the hole and their resistance to earth made exactly the same. One current electrode C_1 and the two potential electrodes P_1P_2 were placed in the hole. The electrodes were moved along the hole at a constant electrode spacing, the potential between P_1P_2 and the current through C_1 being measured at suitable intervals. All surface electrodes were in parallel.

Current electrode C_1 was next left near the bottom of the hole and P_1P_2 moved as a unit along the hole. The potential between P_1P_2 and the current through C_1 were measured at suitable intervals, using in turn each surface electrode as the return current electrode and finally all surface electrodes in parallel for the return current. The values ΔV of the potential between P_1P_2 at

each interval when the current flow was to the north or to the west were taken as the references and the potential when the main current flow was in the other two directions were shown as fractions of these potentials. See Table 1.

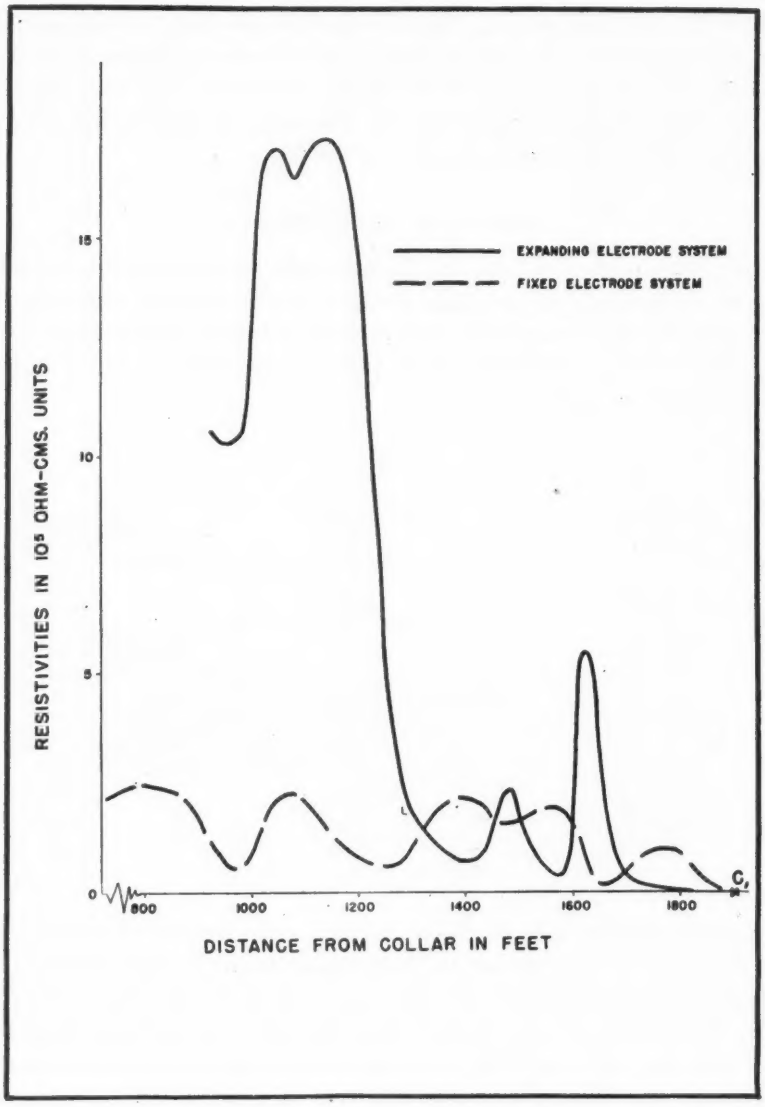

FIG. 4. Resistivity profiles from Drill Hole 57.

CALCULATION OF RESISTIVITIES

Resistivities were calculated on the assumption that the medium was homogeneous from the expression

$$\rho = \frac{4\pi\Delta V}{I} \frac{ab}{b-a}$$

where a and b were the distances $C_1 P_1$ and $C_1 P_2$ respectively. The results thus calculated gave only apparent average resistivities, but the relative magnitude of these values afforded valuable information concerning changes in the conductivity of materials close to the drill hole. The calculated resistivities for constant electrode spacing and for expanding electrode spacing are shown in Figure 4.

DISCUSSION OF RESULTS

The ratios of the $\Delta\overline{V}/\Delta V$ were greater than one should expect from the simple theory for a spherical ore body and indicated very definitely that the ore body was situated to the south and east of the hole. Refer to Table 1.

The apparent average resistivities remained low as long as the theoretically spherical potential shells intersected part of the conductor as shown by the dashed circles and the graph of Figure 3. It is of interest to note that the calculated resistivities increased when the theoretical shells intersected the body where it was interrupted by a known non-conducting sill.

For a small constant electrode spacing the calculated resistivity values were greater than for the expanding electrode spacings, indicating that the low resistivity values were not caused by conductors close to the hole. Thus the two resistivity curves provided a method of separating the effects of conducting bodies such as disseminated sulphide zones at the hole from massive bodies situated some distance away.

CONCLUSIONS

It would appear that the method provides a powerful means of detecting conducting sulphide bodies in the vicinity of drill holes and of determining their extent as well as their distance and direction from the hole.

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A CONDUCTING SPHERE IN A TIME VARYING MAGNETIC FIELD*

JAMES R. WAIT†

ABSTRACT

The secondary magnetic fields are evaluated for the case of a conducting sphere in a relatively poorly conducting medium under the influence of a time varying magnetic field. The sinusoidal and step function responses are both considered. The responses so calculated are thought to be useful in a geophysical prospecting method which utilizes the transient behavior of induced eddy currents in a highly conducting ore zone.

INTRODUCTION

The reaction of a spherical conducting ore zone to an impressed magnetic field is of great practical importance. The general problem of a sphere under the influence of an impressed electromagnetic field has been investigated by Debye (1) in a rather general manner. March (2) has treated the more specific problem of a conducting sphere in the presence of a magnetic dipole.

This paper deals with the special case of a conducting sphere embedded in a relatively poorly conducting medium. The applied field will be assumed to be uniform in the region of the sphere. The secondary fields for sinusoidally varying primary fields will be developed from first principles. This of course is then a special case of the Debye and March solutions when the external medium has a small conductivity. The transient solutions can then be obtained directly by suitable integrations of the steady state solutions. The secondary field responses to a step function type of magnetic applied field are in turn explicitly calculated. M.K.S. units are employed throughout.

DERIVATION OF THE FIELDS

A sphere of radius R will be considered of conductivity σ_1, permeability μ_1, and dielectric constant ϵ_1, in an infinite medium of constants σ_2, μ_2, and ϵ_2. See Figure 1. In the neighborhood of the sphere the applied magnetic field is $H_0 \exp(iwt)$. The statement that the external applied field is uniform requires that the dimensions of the sphere are much less than a wavelength in the external medium. This implies that $|\gamma_2 R| \ll 1$ where γ_2 is the propagation constant of the external medium given by:

$$\gamma_2 = [i\sigma_2\mu_2\omega - \epsilon_2\mu_2\omega^2]^{1/2}.$$

The sphere conductivity σ_1, however, can be quite large and there is no restriction on the parameter $|\gamma_1 R|$ where

$$\gamma_1 = [i\sigma_1\mu_1\omega - \epsilon_1\mu_1\omega^2]^{1/2}.$$

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The center of the sphere is taken as the origin of the spherical polar coordinate system. The polar axis (i.e. z axis) is taken parallel to the applied field.

The magnetic field everywhere must be expressible in terms of the magnetic vector $\overline{F}$ with a z component only since the resulting circulating or eddy currents are only in the ϕ direction.

$$\overline{H} = -(\sigma + i\omega\epsilon)\overline{F} + 1/i\mu\omega \text{ grad div } \overline{F}. \tag{1}$$

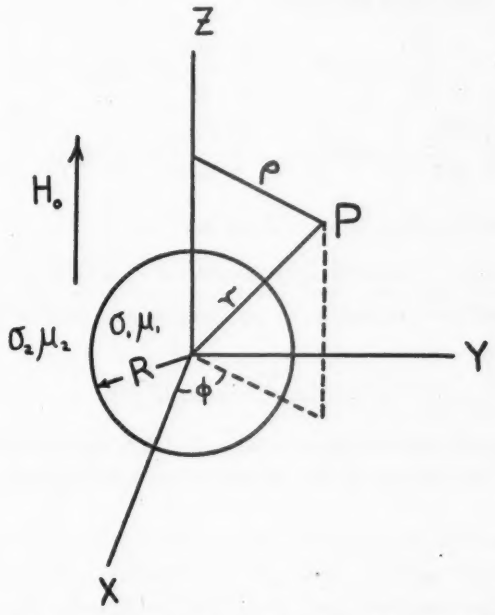

FIG. 1. The coordinate system for the conducting sphere.

The magnetic vector potential $\overline{F}_0$ for the primary field is given by:

$$\overline{F}_0 = F_{0z} = -(\sigma_2 + i\omega\epsilon_2)H_0. \tag{2}$$

The expressions for the magnetic vector $\overline{F}_1$ inside the sphere and $\overline{F}_2$ outside the sphere are then given by:

$$\overline{F}_1 = F_{1z} = \sum_0^\infty \frac{b_n \hat{I}_n(\gamma_1 r)}{r} P_n(\cos\theta) i\mu_1\omega \tag{3}$$

$$\overline{F}_2 = F_{2z} = \sum_0^\infty \frac{a_n \hat{K}_n(\gamma_2 r)}{r} P_n(\cos\theta) i\mu_2\omega - (\sigma_2 + i\omega\epsilon_2)H_0 \tag{4}$$

where $\hat{I}_n(z) = (\alpha z/2)^{1/2} I_{n+1/2}(z)$, $\hat{K}_n(z) = (2z/\alpha)^{1/2} K_{n+1/2}(z)$ and $I_{n+1/2}$ and $K_{n+1/2}$ are modified Bessel functions as defined by Watson (3). The boundary conditions are that tangential magnetic field and the normal flux density are

continuous at $r=R$. This requires that $a_n=b_n=0$ for $n>0$. The expressions are then of the form:

$$F_1 = i\mu_1\omega b_0 \sinh \gamma_1 r/r, \qquad (r \leqq R) \tag{5}$$

and

$$F_2 = -(\sigma_2 + i\omega\epsilon_2)H_0 + i\mu_2\omega a_0 \exp(-\gamma_2 r)/r, \qquad (r \geqq R). \tag{6}$$

The boundary conditions are then:

$$\left.\begin{aligned} \frac{1}{r}\frac{\partial F_1}{\partial r} - \gamma_1^2 F_1 &= \frac{1}{r}\frac{\partial F_2}{\partial r} - \gamma_2^2 F_2 \\ \mu_1\left(\frac{\partial^2 F_1}{\partial r^2} - \gamma_1^2 F_1\right) &= \mu_4\left(\frac{\partial^2 F_2}{\partial r^2} - \gamma_2^2 F_2\right) \end{aligned}\right\} r = R.$$

These equations can then be solved for a_0:

$$a_0 = H_0 R^3\left[\frac{2\mu_1(\sinh\alpha - \alpha\cosh\alpha) + \mu_2(\sinh\alpha - \alpha\cosh\alpha + \alpha^2\sinh\alpha)}{2\mu_1(\sinh\alpha - \alpha\cosh\alpha) - 2\mu_2(\sinh\alpha - \alpha\cosh\alpha + \alpha^2\sinh\alpha)}\right] \tag{7}$$

where

$$\alpha = [i\sigma_1\mu_1\omega - \epsilon_1\mu_1\omega^2]^{1/2}.$$

This result is a special case of the classical problem (4) of a plane wave incident on a sphere when the radius of the sphere R and the parameters are such that $|\gamma_2 R| \ll 1$.

The case of interest is when the sphere conductivity is relatively high compared to the external medium and the permeability contrast is zero (i.e. $\mu_1=\mu_2=\mu=4\pi\times 10^{-7}$). The magnetic and electrical coefficients then reduce to:

$$a_0 = -3/2 H_0 R^3(M + iN) \tag{8}$$

where

$$M + iN = \left[\frac{1}{\alpha_2} + \frac{1}{3} - \frac{\cosh\alpha}{\alpha\sinh\alpha}\right]. \tag{9}$$

The total external magnetic fields are then given by performing the operations

$$H_s(\omega) = -3/2 R^3 H_0(M + iN)(-1/r^3 + 3z^2/r^5) + H_0 \tag{10}$$

and

$$H_\rho(\omega) = 3/2 R^3 H_0(M + iN) 3z\rho/r^5. \tag{11}$$

The in phase factor M and the out of phase component N are plotted in Figure 2 versus the θ given by

$$\theta = (\sigma_1\mu\omega)^{1/2}R$$

where it is assumed that displacement currents are negligible (i.e., $\sigma_1 \gg \epsilon_1\omega$).

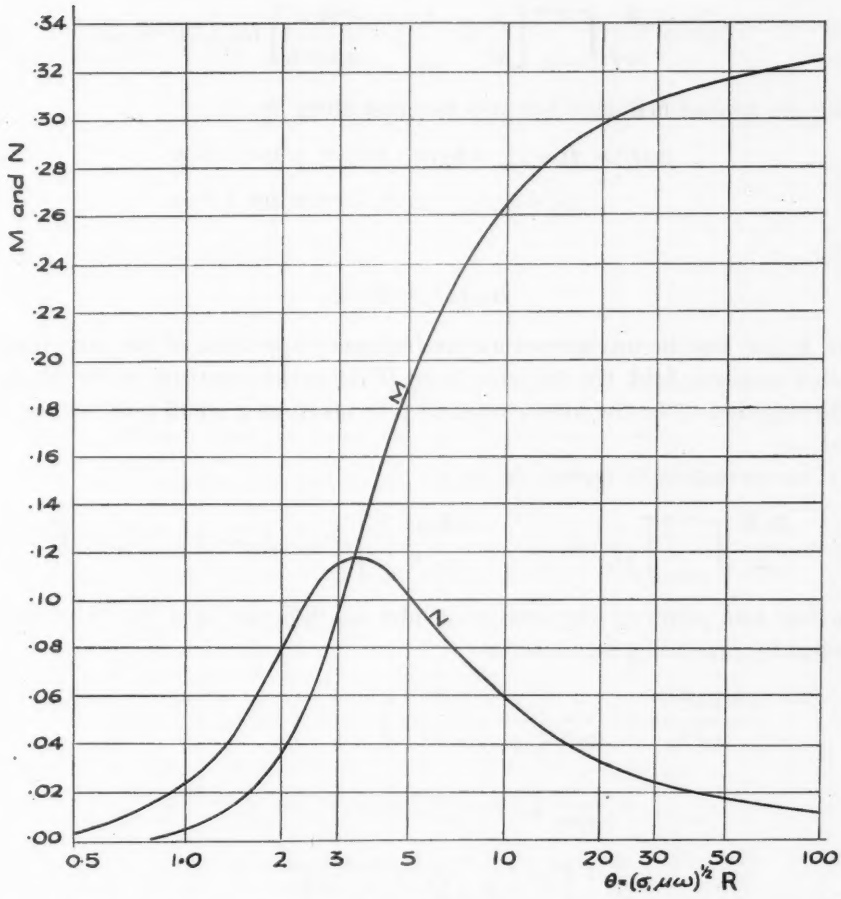

FIG. 2. The behavior of the in phase and out of phase components of the secondary magnetic fields for a sinusoidal type applied field.

The corresponding transient problem can be investigated where again the approximations are made, for important frequencies in the spectrum, that $|\gamma_2 R| \ll 1$ and $\sigma_1 \gg \epsilon_1 \omega$. This will be valid for a step function source magnetic field when the measuring time of the field response is always such that $t \gg \sigma_2 \mu R^2$ and $t \gg \epsilon_1/\sigma_1$.

The steady state response of the secondary field (either H_z or H_ρ component) can be written as follows:

$$H(i\omega) = K\left[\frac{1}{\alpha^2} + \frac{1}{3} - \frac{\cosh \alpha}{\alpha \sinh \alpha}\right] H_0(i\omega) \qquad (12)$$

where K is a constant. The transient field is again given by a Fourier Integral as indicated by the author in a previous paper (5).

$$h(t) = \frac{K}{2\pi i}\int_{c-i\infty}^{c+i\infty}\left[\frac{1}{\alpha^2}+\frac{1}{3}-\frac{\cosh\alpha}{\alpha\sinh\alpha}\right]H_0(i\omega)e^{i\omega t}d(i\omega). \tag{13}$$

When the applied field $h_0(t)$ is a step function given by:

$$h_0(t) = H_1u(t) \quad \text{where} \quad u(t) = 1 \text{ for } t > 0$$
$$= 0 \text{ for } t < 0$$

then

$$H_0(i\omega) = H_0/i\omega.$$

Here $H_0(iw)$ can be interpreted as the frequency spectrum of the step function applied magnetic field. On the other hand $H(iw)$ is the spectrum of the secondary field components. In the above integral C is taken as a small positive real constant.

It is convenient to replace iw by s.

$$h(t) = \frac{H_0K}{2\pi i}\int_{c-i\infty}^{c+i\infty}\left[\frac{1}{\beta^2s^2}+\frac{1}{s}-\frac{\coth\beta s^{1/2}}{\beta s^{3/2}}\right]e^{st}ds \text{ where } \beta = (\sigma_1\mu)^{1/2}R. \tag{14}$$

The first two terms in the integrand offer no difficulty and the third term is handled by expanding into a series

$$\frac{\coth\beta s^{1/2}}{\beta s^{3/2}} = \frac{1}{\beta s^{3/2}}\left[\frac{1+e^{-2\beta s^{1/2}}}{1-e^{-2\beta s^{1/2}}}\right]$$
$$= \frac{1}{\beta s^{3/2}}\left[1+e^{-2\beta s^{1/2}}+e^{-4\beta s^{1/2}}+e^{-2\beta s^{1/2}}+\cdots\right]$$
$$= \frac{1}{\beta}\left[\frac{1}{s^{3/2}}+2\sum_1^\infty\frac{e^{-2n\beta s^{1/2}}}{s^{3/2}}\right]. \tag{15}$$

This then gives rise to an infinite series of integrals of the following type (6):

$$\frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty}s^{-3/2}e^{-ks^{1/2}}e^{st}ds = k\left[t^{1/2}/k\ \text{erf}'\ (kt^{-1/2}/2) - \text{erfc}\ (kt^{-1/2}/2)\right].$$

The transient response is then given by

$$F(t) = \frac{h(t)}{K} = x^2 + 1/3 - 2\pi^{-1/2}x - \sum_1^\infty 2n\left[x/n\ \text{erf}'\ (n/x) - 2\ \text{erfc}\ (n/x)\right] \tag{16}$$

where

$$x = t^{1/2}/\beta = t^{1/2}/(\sigma\mu)^{1/2}R$$

In the above expressions erf′ and erfc are the first derivative and the complement of the Error functions as defined by Jahnke and Emde (7). The secondary field

responses at a point P outside the sphere due to an exciting step function source field at the sphere is then given by

$$h_z(t) = 3/2R^3H_1F(t)\left[1/r^3 - 3z^2/r^5\right]u(t) \tag{17}$$

and

$$h_\rho(t) = 3/2R^3H_1F(t)3z\rho/r^5u(t). \tag{18}$$

The function $F(t)$ is plotted in Figure 3.

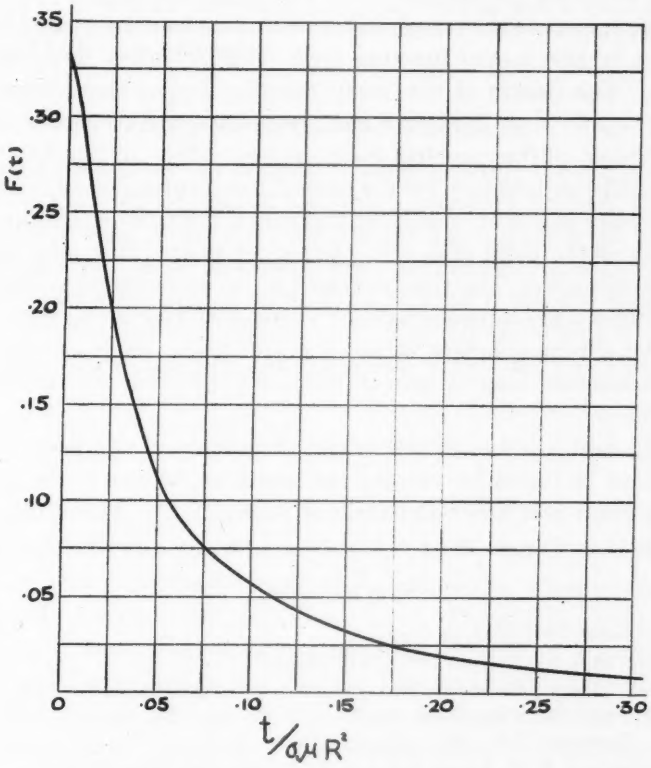

FIG. 3. The transient behavior of the secondary magnetic field for a step function type applied field.

SIGNIFICANCE OF RESULTS

The steady state solutions will be discussed first. In Figure 2 the function $M+iN$ is plotted versus a frequency parameter θ. The secondary external fields are seen by equations (10) and (11) to be both proportional to the complex factor $M+iN$. The behavior of the secondary field as the circular frequency is varied is the same regardless of the position of the observer. It would then seem feasible

that this could be the basis of a geophysical method to ascertain the conductivity or radius of the embedded sphere.

It would be necessary in this case to simply obtain the behavior of either the in phase or out of phase component of the secondary field whence the parameter $\sigma_1\mu R^2$ could be obtained. A local field could be set up by any suitable ungrounded wire loop arrangement. The secondary fields are then obtained by receiving loops. The primary field, of course, must also be accounted for in measuring the in phase component of the secondary field.

The parameter $\sigma_1\mu R^2$ might also be found directly by measuring the magnetic field response following the application of a step function current (i.e. a suddenly applied direct current) to the transmitting or sending loops. The applied magnetic field will then be also a step function type. The secondary fields are given by (17) and (18). The nature of the decay function $F(t)$ is characteristic only on the parameter $\sigma_1\mu R^2$ when the above mentioned approximations are valid.

The conditions of this problem have seemed rather stringent. The solution however should be satisfactory for the case of a large massive sulphide body with a conductivity say of $\sigma_1 = 10^2$ mhos per meter in a surrounding country rock with a conductivity of the order of $\sigma_2 = 10^{-3}$ mhos per meter. The body might have a radius of say 20 meters. The time constant of decay of the secondary magnetic field (where $F(t) = 0.12$) is then equal to 2.4 milliseconds. For this case the primary field will have a time constant of the order of a few microseconds, that is, it approaches a constant value almost immediately following the application of the source current.

The depth and location of the center of gravity of the body on the other hand could best be found by varying the geometry factors of the receiving and transmitting loops and observing the variations of the magnitudes of the secondary fields as is done in more conventional methods of electrical prospecting.

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ELASTIC WAVES THROUGH A PACKING OF SPHERES*

FRITZ GASSMANN†

ABSTRACT

Based on a theory of porous solids previously developed by the author, the elasticity of a hexagonal close packing of equal spheres is treated. The packing is anisotropic and because of the weight of the spheres, also inhomogeneous. The velocities of propagation of elastic waves have been calculated for evacuated interspaces and for interspaces filled with a liquid or gas. In the case of evacuated or air-filled interspaces, the wave rays and travel times have been computed. The packing which has been treated may be of use as a model for a dry or wet loose material such as gravel or sand. Though the model is very simplified, the results obtained show some typical effects such as anisotropy, inhomogeneity, and a 90° angle of emergence.

THE ELASTICITY OF POROUS SOLIDS

In a previous paper by the author (Gassmann, 1951) the elasticity of homogeneous isotropic or anisotropic porous solids has been treated. The following investigations are based upon the results of the above mentioned paper. Therefore these results may first be summarized, all demonstrations being omitted.

A sample of a porous solid possessing the volume V and the mass m, may be composed of a homogeneous isotropic solid material of volume $\hat{V}$ and mass $\hat{m}$ and of a homogeneous liquid or gas of volume $\tilde{V}$ and mass $\tilde{m}$ filling the pores. Therefore,

$$V = \hat{V} + \tilde{V}, \qquad m = \hat{m} + \tilde{m}, \qquad n = \frac{\tilde{V}}{V} = \text{porosity}. \tag{1}$$

Macroscopically the porous solid may be considered as a homogeneous elastic solid if the pores are assumed sufficiently small. Though the solid material is assumed isotropic, the porous solid can behave either as an isotropic or anisotropic elastic body according to the shape of the pores. All pores are assumed to be in connection. Let us consider an initial state of stress and strain (e.g. such as the state of rocks under the weight of overlying material) and variations from this state small enough to allow the application of Hooke's law. Two extreme cases will be taken into account. In the first case the variations of stress act only upon the solid matter, the hydrostatic pressure of the pore content remaining constant, due to circulation allowed through the pores and through the surface of the body. The porous solid then behaves like an "open system" (e.g., slow variations of stress applied to a rock sample in free air). In the second case circulation of the pore content is not possible, the porous solid behaving like a "closed

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system" (e.g., stress variations in the earth's interior due to earthquake waves). Notations:

x, y, z = rectangular coordinates

s_x, s_y, s_z = rectangular components of displacement (Love, 1944), due to stress variations.

Δe_i = components of strain variations.

$$\Delta e_1 = \frac{\partial s_x}{\partial x}, \qquad \Delta e_2 = \frac{\partial s_y}{\partial y}, \qquad \Delta e_3 = \frac{\partial s_z}{\partial z}$$
$$\Delta e_4 = \frac{\partial s_y}{\partial z} + \frac{\partial s_z}{\partial y}, \qquad \Delta e_5 = \frac{\partial s_z}{\partial x} + \frac{\partial s_x}{\partial z}, \qquad \Delta e_6 = \frac{\partial s_x}{\partial y} + \frac{\partial s_y}{\partial x} \tag{2}$$

$\Delta \bar{p}_i, \Delta p_i$ = components of stress variations of the open and the closed system (pressure with positive sign).

$$\hat{\lambda}, \hat{\mu}, \hat{k} = \hat{\lambda} + \frac{2}{3}\hat{\mu} \tag{3}$$

Lame's constants and modulus of compression of the solid material.

$\tilde{k}$ = modulus of compression of the pore content. Stress-strain relations, general anisotropic case:

open system:

$$\Delta \bar{p}_i = -\sum_{j=1}^{6} \bar{c}_{ij}\Delta e_j \begin{cases} i = 1, 2, \cdots, 6 \\ j = 1, 2, \cdots, 6 \end{cases}$$
$$\Delta e_i = -\sum_{j=1}^{6} \bar{\gamma}_{ij}\Delta \bar{p}_j, \qquad \bar{c}_{ij} = \bar{c}_{ji}, \qquad \bar{\gamma}_{ij} = \bar{\gamma}_{ji} \tag{4}$$

closed system:

$$\Delta p_i = -\sum_{j=1}^{6} c_{ij}\Delta e_j, \qquad \Delta e_i = -\sum_{j=1}^{6} \gamma_{ij}\Delta p_j \tag{5}$$
$$c_{ij} = c_{ji}, \qquad \gamma_{ij} = \gamma_{ji}.$$

Relations between the elastic constants:

$$c_{ij} = \bar{c}_{ij} + \frac{\alpha^*}{D^*} b_i b_j \tag{6}$$

$$\gamma_{ij} = \bar{\gamma}_{ij} - \frac{\alpha^*}{D} a_i a_j$$

$$\alpha^* = \frac{1}{n\left(\frac{1}{\tilde{k}} - \frac{1}{\hat{k}}\right)} \tag{7}$$

$$\epsilon_1 = \epsilon_2 = \epsilon_3 = 1, \qquad \epsilon_4 = \epsilon_5 = \epsilon_6 = 0$$

$$a_i = \bar{\gamma}_{i1} + \bar{\gamma}_{i2} + \bar{\gamma}_{i3} - \frac{\epsilon_i}{3\hat{k}}$$

$$b_i = \epsilon_i - \frac{1}{3\hat{k}}(\bar{c}_{i1} + \bar{c}_{i2} + \bar{c}_{i3})$$

$$D = 1 + \alpha^*(a_1 + a_2 + a_3)$$

$$D^* = 1 + \frac{\alpha^*}{3\hat{k}}(b_1 + b_2 + b_3).$$

In particular, for the isotropic case:

$\bar{\lambda}, \bar{\mu}, \bar{k} = \bar{\lambda} + \frac{2}{3}\bar{\mu}$ elastic constants of the open system.

$\lambda, \mu, k = \lambda + \frac{2}{3}\mu$ elastic constants of the closed system.

From (7) is obtained

$$\mu = \bar{\mu} \qquad k = \hat{k}\cdot\frac{\bar{k} + Q}{\hat{k} + Q} \qquad Q = \frac{\tilde{k}(\hat{k} - \bar{k})}{n(\hat{k} - \tilde{k})} \tag{8}$$

HEXAGONAL CLOSE PACKING OF SPHERES, HOMOGENEOUSLY STRESSED

Let two homogeneous and isotropic spheres of equal radius R (with Lamé's constants $\hat{\lambda}$, $\hat{\mu}$) be in contact under the pressure P (Figure 1).

$$\hat{E} = \frac{\hat{\mu}(3\hat{\lambda} + 2\hat{\mu})}{\hat{\lambda} + \hat{\mu}} = \text{Young's modulus},$$

$$\hat{\nu} = \frac{\hat{\lambda}}{2(\hat{\lambda} + \hat{\mu})} = \text{Poisson's ratio}.$$

According to Hertz's theory (Love, 1944), the radius of the circle of contact is

$$R' = \sqrt[3]{\frac{3(1 - \hat{\nu})^2 R}{4\hat{E}}}\,P. \tag{9}$$

R' is assumed to be small compared with R, and

$$s \cong \frac{R'^2}{R} = \sqrt[3]{\frac{9(1 - \hat{\nu}^2)^2 P^2}{16\hat{E}^2 R}} = \text{relative displacement of the spheres.} \tag{10}$$

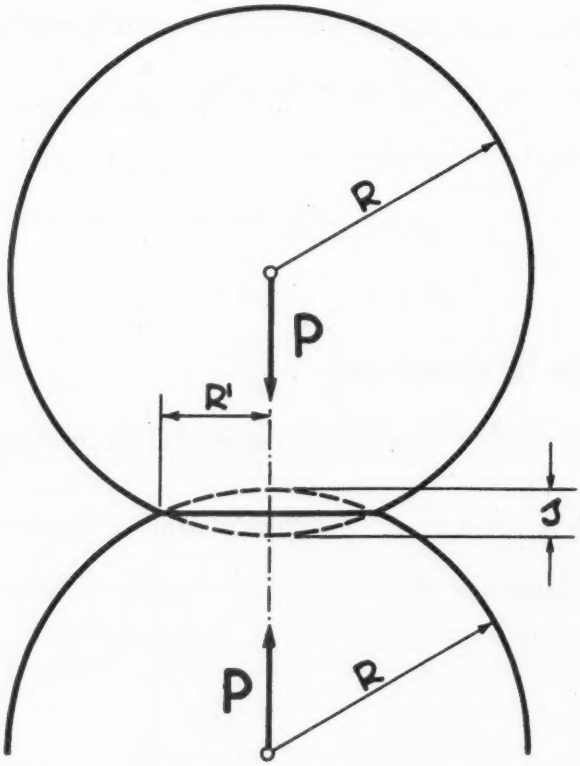

FIG. 1. Two equal spheres in contact.

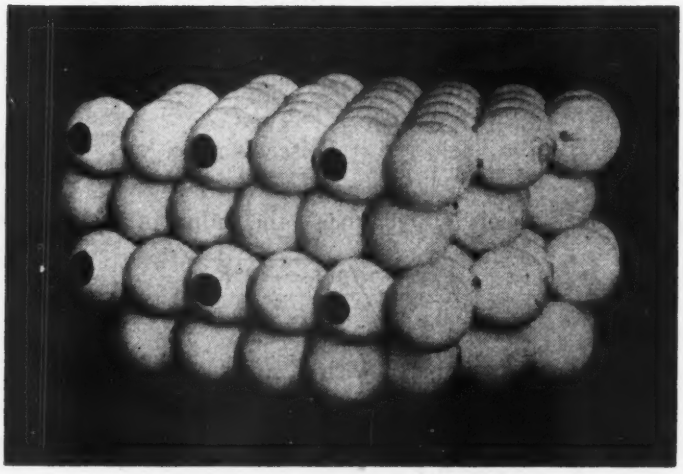

FIG. 2. The hexagonal close packing of spheres.

The hexagonal close packing of equal spheres (Figure 2) now to be considered (following an idea of Hara, 1935) consists of different layers (Figure 3). The coordinates of the centers of the spheres belonging to the Nth layer (no pressure assumed) are

$$x = \frac{R}{2}\left[4N' + 2N'' + (-1)^N + 1\right]$$
$$y = \frac{\sqrt{3}\,R}{4}\left[4N'' + (-1)^N + 1\right] \tag{11}$$
$$z = \frac{2\sqrt{6}}{3}RN, \qquad N' \text{ and } N'' \text{ being arbitrary real integers.}$$

As initial stress, we assume zero pressure between the spheres of the same layer,

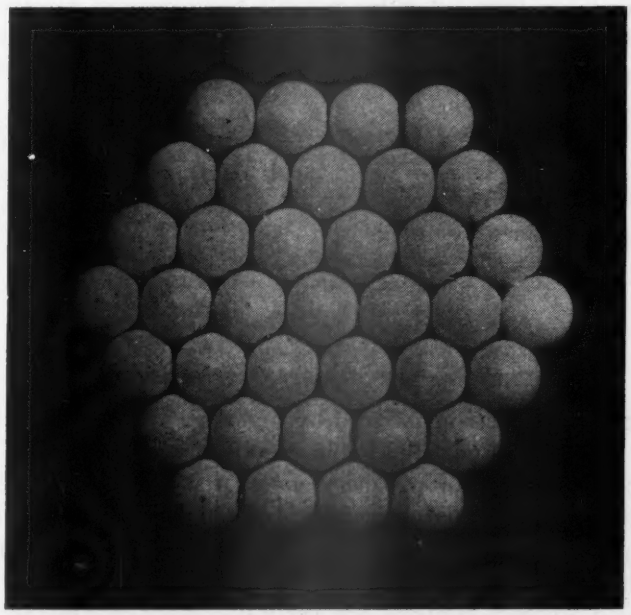

FIG. 3. A layer of spheres of the hexagonal close packing.

i.e., the spheres with centres of the same value of z, and a pressure $P>O$ between each pair of spheres in contact, belonging to neighboring layers. The corresponding slight deformation of the lattice (11) of the centers can be neglected in the following considerations. If the number of layers and spheres is sufficiently large, the packing at its initial state of stress can be considered as a homogeneous anisotropic porous solid

$$\left[\text{porosity } n = 1 - \frac{\pi}{3\sqrt{2}} = 0.260\right] \tag{12}$$

with the symmetry of Voigt's class Nr. 26 of crystals. With respect to elasticity all directions perpendicular to z are equivalent ("transversely isotropic" symmetry, Love 1944, page 160) and the elasticity is determined by five constants $C_1, C_2, \ldots, C_5$, the matrix of the open system constants $\bar{c}_{ij}$ in (4) taking the form

$$\begin{Bmatrix} C_1 & C_1-2C_5 & C_2 & 0 & 0 & 0 \\ C_1-2C_5 & C_1 & C_2 & 0 & 0 & 0 \\ C_2 & C_2 & C_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & C_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & C_4 & 0 \\ 0 & 0 & 0 & 0 & 0 & C_5 \end{Bmatrix}. \tag{13}$$

The $\bar{c}_{ij}$ can be taken from (4), if for suitable homogeneous deformations of the lattice (11) the variations of stress are calculated by means of (10), variations Δs and ΔP being replaced by ds and dP. With

$$\bar{c} = \frac{1}{12\sqrt{2}} \cdot \frac{1}{R} \cdot \frac{dP}{ds} = \frac{1}{12\sqrt{2}} \cdot \sqrt[3]{\frac{6\widehat{E}^2 P}{(1-\hat{\nu}^2)^2 R^2}} \tag{14}$$

the matrix $\bar{c}_{ij}$ is obtained by putting

$$C_1 = \bar{c}, \qquad C_2 = C_4 = 4\bar{c}, \qquad C_3 = 16\bar{c}, \qquad C_5 = 0 \tag{15}$$

into (13).

THE PACKING OF SPHERES STRESSED BY SELF-WEIGHT

The packing of spheres introduced by Figures 2 and 3 and the formulas (11) may now be considered under the influence of self-weight, the $+z$ axis pointing vertically downward. The interspaces between the spheres may be filled with a liquid of constant density $\tilde{\rho}$. Each sphere belonging to the Nth layer is in contact with three spheres of the $(N+1)$th layer under the pressure P_N and with three spheres of the $(N-1)$th layer under the pressure P_{N-1}. The condition for equilibrium of such a sphere contains the vertical components of the six pressures, and the apparent weight $4\pi/3R^3(\hat{\rho}-\tilde{\rho})g$ of the sphere when $g=980.665$ cm sec^{-2}. It is

$$P_{N-1}\cdot\sqrt{6} - P_N\cdot\sqrt{6} + \frac{4\pi}{3} R^3(\hat{\rho}-\tilde{\rho})g = 0. \tag{16}$$

If no load is assumed above the first layer, then $P_0=0$ and the recurrence formula (16) leads to

$$P_N = N\cdot\frac{4\pi}{3\sqrt{6}} R^3(\hat{\rho}-\tilde{\rho})g \tag{17}$$

or taking the value of N from (11):

$$P_N = \frac{\pi}{3} R^2(\hat{\rho} - \tilde{\rho})gz. \tag{18}$$

Substituting this expression for P in (14), we obtain

$$\bar{c} = \frac{1}{12\sqrt{2}} \sqrt[3]{\frac{2\pi\hat{E}^2(\hat{\rho} - \tilde{\rho})g}{(1 - \hat{\nu}^2)^2}} \cdot \sqrt[3]{z}. \tag{19}$$

If the pores are filled with a liquid, the packing of spheres may be called a "wet system." If the pores are evacuated [$\tilde{\rho} = 0$], the packing may be called a "dry system." If the pores are filled with air, its density and its modulus of compression are negligible. Therefore the system possesses the elasticity of a dry system.

$$\begin{aligned} \bar{\rho} &= (1 - n)\hat{\rho} = \text{density of the dry system.} \\ \rho &= (1 - n)\hat{\rho} + n\tilde{\rho} = \text{density of the wet system.} \\ &\quad (n = 0.26, \text{ see } (12)). \end{aligned} \tag{20}$$

The stress below the plane $z = z_0 > 0$ (z_0 large compared with R) is not changed if the packing of spheres between the planes $z = 0$ and $z = z_0$ is replaced by an arbitrary layer between the planes $z = z_1$ and $z = z_0$, with density ρ^*, depending only on z, if

$$\int_{z_1}^{z_0} \rho^*(z)dz = \rho z_0. \tag{21}$$

The packing of spheres may be considered as a simple model for a gravel or sand, dry (= dry system) or filled with ground water (= wet system).

PROPAGATION OF ELASTIC WAVES THROUGH THE PACKING OF SPHERES

The elasticity of the dry system is given by the matrix of the $\bar{c}_{ij}$ which is calculated by means of (13), (15) and (19) with $\tilde{\rho} = 0$. In order to calculate the elastic constants of the closed wet system, first the matrix of the $\bar{c}_{ij}$ is calculated in the same way, but with $\tilde{\rho} \neq 0$ in $\bar{c}$ of (19). Then the matrix of the c_{ij}, found by (6), is the matrix (13) with

$$\begin{aligned} C_1 &= \bar{c} + \frac{\alpha^*}{D^*} b_1^2, \qquad C_2 = 4\bar{c} + \frac{\alpha^*}{D^*} b_1 b_3, \\ C_3 &= 16\bar{c} + \frac{\alpha^*}{D^*} b_3^2, \qquad C_4 = 4\bar{c}, \qquad C_5 = 0, \\ &\left(b_1 = b_2 = 1 - 2\frac{\bar{c}}{\hat{k}}, \quad b_3 = 1 - 8\frac{\bar{c}}{\hat{k}}, \quad b_4 = b_5 = b_6 = 0\right). \end{aligned} \tag{22}$$

The partial differential equations of wave motion, the wave length assumed

large compared with R, are obtained by substituting the stress-strain relations into the general equations of motion of an elastic solid (Love, 1944):

$$\begin{aligned}
\rho\frac{\partial^2 s_x}{\partial t^2} &= C_1\frac{\partial^2 s_x}{\partial x^2} + C_5\frac{\partial^2 s_x}{\partial y^2} + C_4\frac{\partial^2 s_x}{\partial z^2} + (C_1 - C_5)\frac{\partial^2 s_y}{\partial x\partial y} \\
&\quad + (C_2 + C_4)\frac{\partial^2 s_z}{\partial x\partial z}, \\
\rho\frac{\partial^2 s_y}{\partial t^2} &= C_5\frac{\partial^2 s_y}{\partial x^2} + C_1\frac{\partial^2 s_y}{\partial y^2} + C_4\frac{\partial^2 s_y}{\partial z^2} + (C_2 + C_4)\frac{\partial^2 s_z}{\partial y\partial z} \\
&\quad + (C_1 - C_5)\frac{\partial^2 s_x}{\partial x\partial y}, \\
\rho\frac{\partial^2 s_z}{\partial t^2} &= C_4\frac{\partial^2 s_z}{\partial x^2} + C_4\frac{\partial^2 s_z}{\partial y^2} + C_3\frac{\partial^2 s_z}{\partial z^2} + (C_2 + C_4)\frac{\partial^2 s_x}{\partial x\partial z} \\
&\quad + (C_2 + C_4)\frac{\partial^2 s_y}{\partial y\partial z},
\end{aligned} \tag{23}$$

where t = time. For the wet system, the C_i's are to be taken from (22), for the dry system from (15), putting $\tilde{p}=0$ in (19) and (20). Now let $W(x, y, z, t)$ = const. = equation of a wave front.

$$\frac{\partial W}{\partial t} = q_0, \quad \frac{\partial W}{\partial x} = q_1, \quad \frac{\partial W}{\partial y} = q_2, \quad \frac{\partial W}{\partial z} = q_3. \tag{24}$$

The characteristic relation (Levi-Cività, 1932) of the system (23) is

$$\begin{vmatrix} A_{11} - \rho q_0^2 & A_{12} & A_{13} \\ A_{12} & A_{22} - \rho q_0^2 & A_{23} \\ A_{13} & A_{23} & A_{33} - \rho q_0^2 \end{vmatrix} = 0, \tag{25}$$

$$\begin{aligned}
A_{11} &= C_1 q_1^2 + C_5 q_2^2 + C_4 q_3^2, & A_{12} &= (C_1 - C_5) q_1 q_2, \\
A_{22} &= C_5 q_1^2 + C_1 q_2^2 + C_4 q_3^2, & A_{23} &= (C_2 + C_4) q_2 q_3, \\
A_{33} &= C_4 q_1^2 + C_4 q_2^2 + C_3 q_3^2, & A_{13} &= (C_2 + C_4) q_1 q_3.
\end{aligned}$$

Assuming a point source (= focus) at $x=y=z=0$ and considering the wave propagation in the (x,z) plane, we have by reason of symmetry, $q_2=0$

$$v = \left| \frac{q_0}{\sqrt{q_1^2 + q_3^2}} \right| = \text{velocity of propagation perpendicular to the wave front.} \tag{26}$$

$\tan\alpha = \dfrac{q_1}{q_3}$, α = angle between the normal of the wave front and the z axis.

The three roots of (25) corresponding to the three different kinds of waves with velocities $v=v_1,\ v_2,\ v_3$ lead to

$$\left.\begin{matrix} v_1^2 \\ v_2^2 \end{matrix}\right\} = \frac{1}{2\rho(q_1^2+q_3^2)}\left(A_{11}+A_{33} \pm \sqrt{A_{11}^2+A_{33}^2+4A_{13}^2-2A_{11}A_{33}}\right) \tag{27}$$

$$v_3^2 = \frac{A_{22}}{\rho(q_1^2+q_3^2)}.$$

As an example, the velocity $v_1 (v_1>v_2>v_3)$ has been calculated for a packing of granitic spheres, dry $[v_1=v_1(z,\alpha)]$ and filled with water $[v_1=v_1^*(z,\alpha)]$ for $\alpha=0°$ (vertical direction of propagation) and $\alpha=90°$ (horizontal direction), using the following values:

$$\hat{\rho} = 2.65\ \frac{\text{gr}}{\text{cm}^3}, \qquad \hat{E} = 0.5\cdot 10^{12}\ \frac{\text{dyne}}{\text{cm}^2}, \qquad \hat{\nu} = 0.25,$$

$$\tilde{\rho} = \begin{cases} 0 & \text{dry}, \\ 1\ \dfrac{\text{gr}}{\text{cm}^3} & \text{wet}, \end{cases} \qquad \tilde{k} = 2.06\cdot 10^{10}\ \frac{\text{dyne}}{\text{cm}^2}. \tag{28}$$

The results are shown in Figure 4.

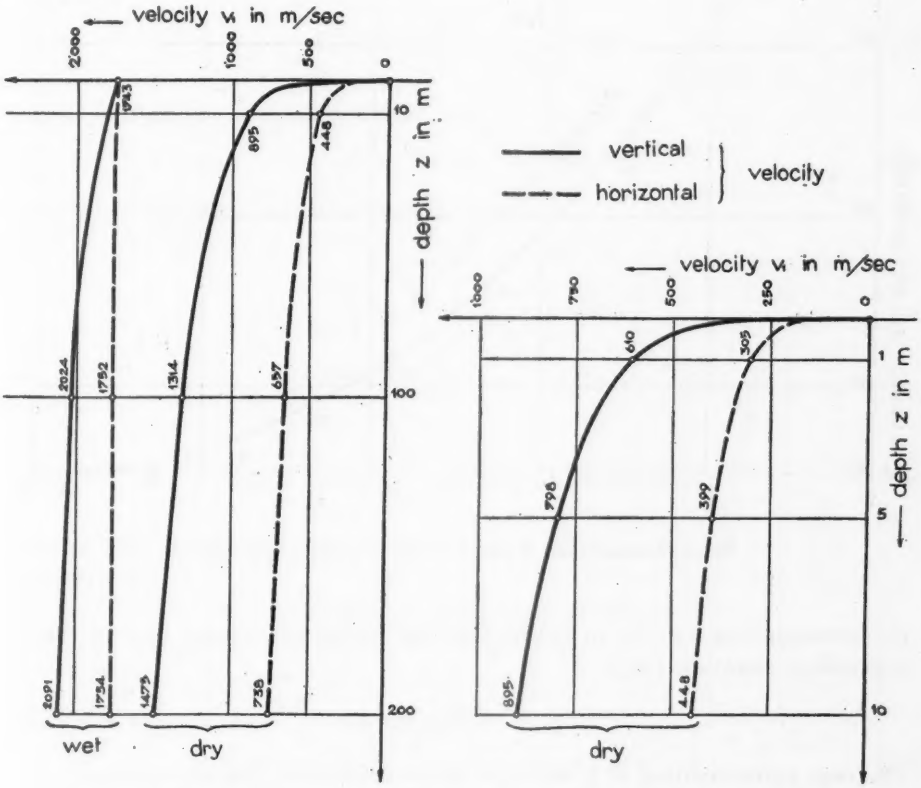

FIG. 4. Velocities of wave propagation in a packing of spheres.

The wave rays (=seismic rays) are the bi-characteristics of (23). For the rays in the (x,z) plane ($q_2=0$), the differential equations are:

$$\frac{dx}{dt}=\frac{\partial H}{\partial q_1}, \qquad \frac{dz}{dt}=\frac{\partial H}{\partial q_3},$$
$$\frac{dq_1}{dt}=-\frac{\partial H}{\partial x}, \qquad \frac{dq_3}{dt}=-\frac{\partial H}{\partial z}, \qquad \frac{dq_0}{dt}=-\frac{\partial H}{\partial t}. \tag{29}$$

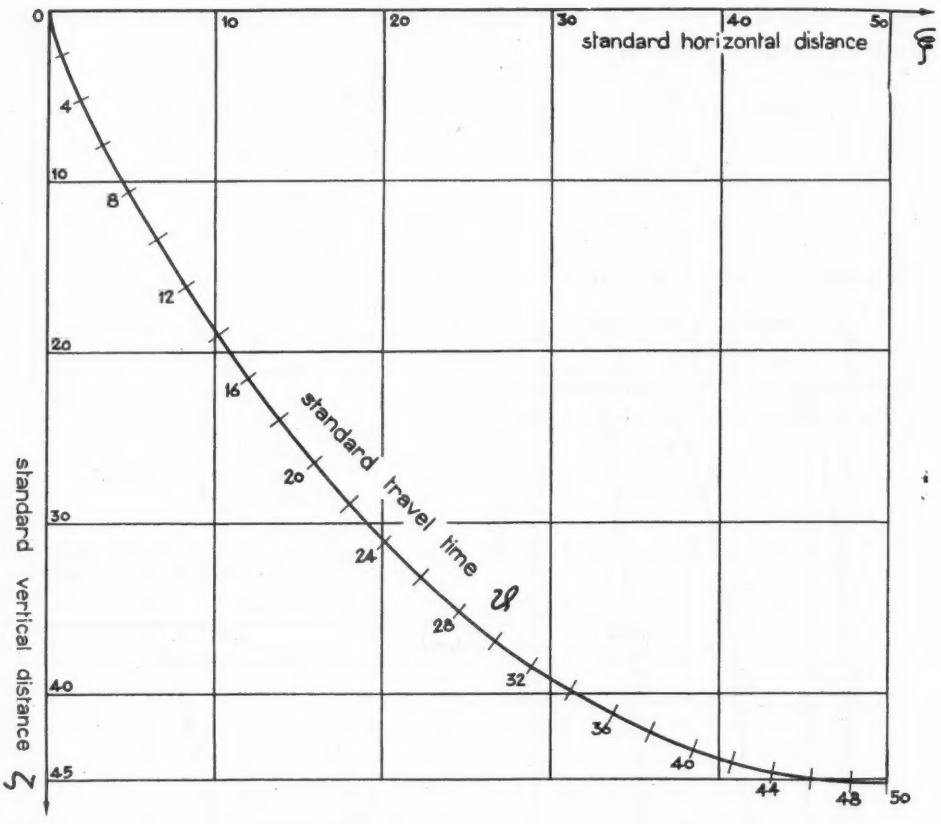

FIG. 5. Standard ray of elastic waves in a packing of spheres.

H, corresponding e.g., to v_1, is obtained by taking the square root of the corresponding equation (27):

$$q_0 = -H(z, q_1, q_3). \tag{30}$$

The rays corresponding to v_1 will now be calculated for the dry system:

$$H = \frac{L}{4\sqrt{2}} \cdot \sqrt[6]{z} \sqrt{5(q_1^2 + 4q_3^2) + \sqrt{9q_1^4 + 328q_1^2q_3^2 + 144q_3^4}},$$
$$L = \sqrt[3]{\frac{8\hat{E}\sqrt{2g}}{\pi\hat{\rho}(1 - \hat{\nu}^2)}}. \tag{31}$$

We introduce α as parameter

$$F(\alpha) = \frac{1}{8}\sqrt{25 + 15\cos 2\alpha + \sqrt{(15 + 9\cos 2\alpha)^2 + 256\sin^2 2\alpha}},$$
$$\frac{dF}{d\alpha} = F'(\alpha), \tag{32}$$
$$v_1 = L \cdot \sqrt[6]{z} \cdot F(\alpha),$$
$$H = L \cdot \sqrt[6]{z} \cdot \frac{F(\alpha)}{\sin\alpha} \cdot q_1$$

and integrate (29).
If $t = 0$ is assumed as focal time, the results are:

$$T(\alpha) = 5\int_0^\alpha \frac{\sin^4\psi}{[F(\psi)]^6}\, d\psi \tag{33}$$

(auxiliary function, graphically computed)

$$T_1 = T(\pi) = 141{,}950 \tag{34}$$

(integration by aid of elliptic integrals)
Standard ray (Figure 5):

$$\xi = \frac{100}{T_1}\left\{T(\alpha) - \left[\frac{\sin\alpha}{F(\alpha)}\right]^6 \cdot \cot\alpha\right\}$$
$$\zeta = \frac{100}{T_1}\left[\frac{\sin\alpha}{F(\alpha)}\right]^6 \tag{35}$$
$$\vartheta = \frac{100}{T_1} \cdot T(\alpha) \quad (=\text{standard travel time})$$

angle of emergence $= 90°$
Arbitrary ray:

a = horizontal focal distance of the ray.

$$x = \frac{a}{100}\xi, \qquad z = \frac{a}{100}\zeta,$$
$$t = 0.012\sqrt[6]{T_1} \cdot \frac{a^{5/6}}{L} \cdot \vartheta = 0.027408 \cdot \frac{a^{5/6}}{L} \cdot \vartheta \cdot \tag{36}$$

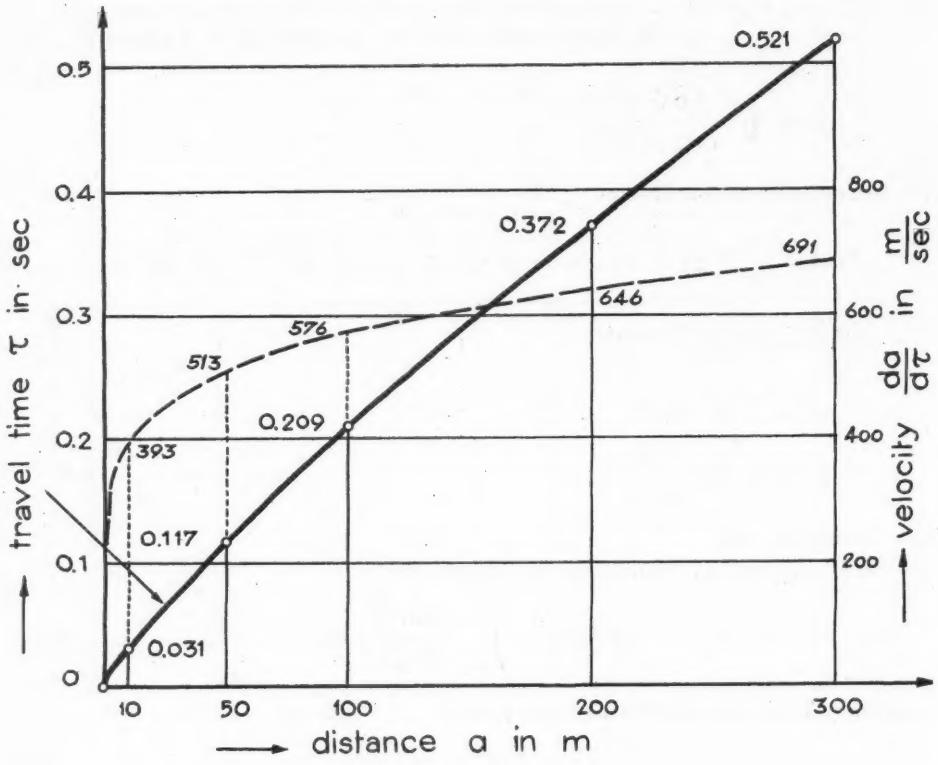

FIG. 6. Travel time and apparent velocity of elastic waves in a packing of spheres.

The ray is symmetric with respect to $x=a/2$.
Travel time function:

$$\alpha = \pi, \quad x = a, \quad z = 0, \quad t = \tau = \frac{2.7408}{L} a^{5/6} \quad \text{(Figure 6)}. \tag{37}$$

Deepest point of the ray:

$$\alpha = \frac{\pi}{2}, \quad x = \frac{a}{2}, \quad z = z_s = \frac{64}{T_1} a = 0.451a. \tag{38}$$

ACKNOWLEDGMENTS

The integration of (29) and the evaluation of (34) have been carried out by Dr. Oswald Wyler, and the other numerical computations by Dr. Oswald Wyler and Walter Kellenberger, both as assistants in the Geophysical Department of the Swiss Federal Institute of Technology. The models shown in Figures 2 and

3 belong to the Mineralogical Department of the Institute, and I would like to thank Prof. P. Niggli for permission to photograph them.

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LEAST SQUARES RESIDUAL ANOMALY DETERMINATION*

W. B. AGOCS†

ABSTRACT

The residual anomaly is defined as the deviation from the mean anomaly surface, or the regional surface. The regional surface which best fits the observed anomaly data may be determined by least squares. For the case of the simple plane, the equation of the regional would be $Z=Ax+By+C$, and the residual anomaly would be $R=G-Z=G-(Ax+By+C)$, where G is the observed value at the station whose coordinates are x, y. The constants of the equation of the regional may be determined by using the normalizing equations $\sum R\partial R/\partial A=0$; $\sum R\partial R/\partial B=0$; $\sum R\partial R/\partial C=0$. It is shown that for a symmetrical distribution of observational points about a center, the regional value at the center would be equal to $\sum_1^n G_n/n$ and this value subtracted from the central point is the residual. Given the coordinates and the observed values, the regional may be determined, and the residual for the area calculated rapidly. An example is given of the procedure.

INTRODUCTION

The data mapping potential fields is an integrated effect of all sources causing an observed anomaly. In applied geophysics the problem is to eliminate or reduce to a minimum the effects of deep-seated, non-commercial sources with as little distortion of the resultant anomaly as possible. The major field effect which is eliminated is the massive *regional*, and the minor deviations of the observed data from this regional is the *residual* anomaly. Numerous mention has been made of the value of eliminating the regional and using the residual in interpretation procedure, but there is a paucity of general information on the subject.

The residual anomaly determination is to be studied and discussed in the following. The residual anomaly may be defined as the deviation from the mean or regional field surface. This may be defined mathematically as

$$R = G - Z \tag{1}$$

where R is the residual anomaly, G is the observed anomaly, and Z is the regional.

The methods of determining the regional for an area from which the residual is determined are numerous, and the value of the residual map is dependent on the knowledge of the method used to determine the regional and the assumptions underlying the choice of method. In the following the various methods in use are discussed, although combinations of the methods are frequently used.

REGIONAL AND RESIDUAL DETERMINATION

Arithmetic Mean

One of the simplest and most rapid means of obtaining the regional is by the

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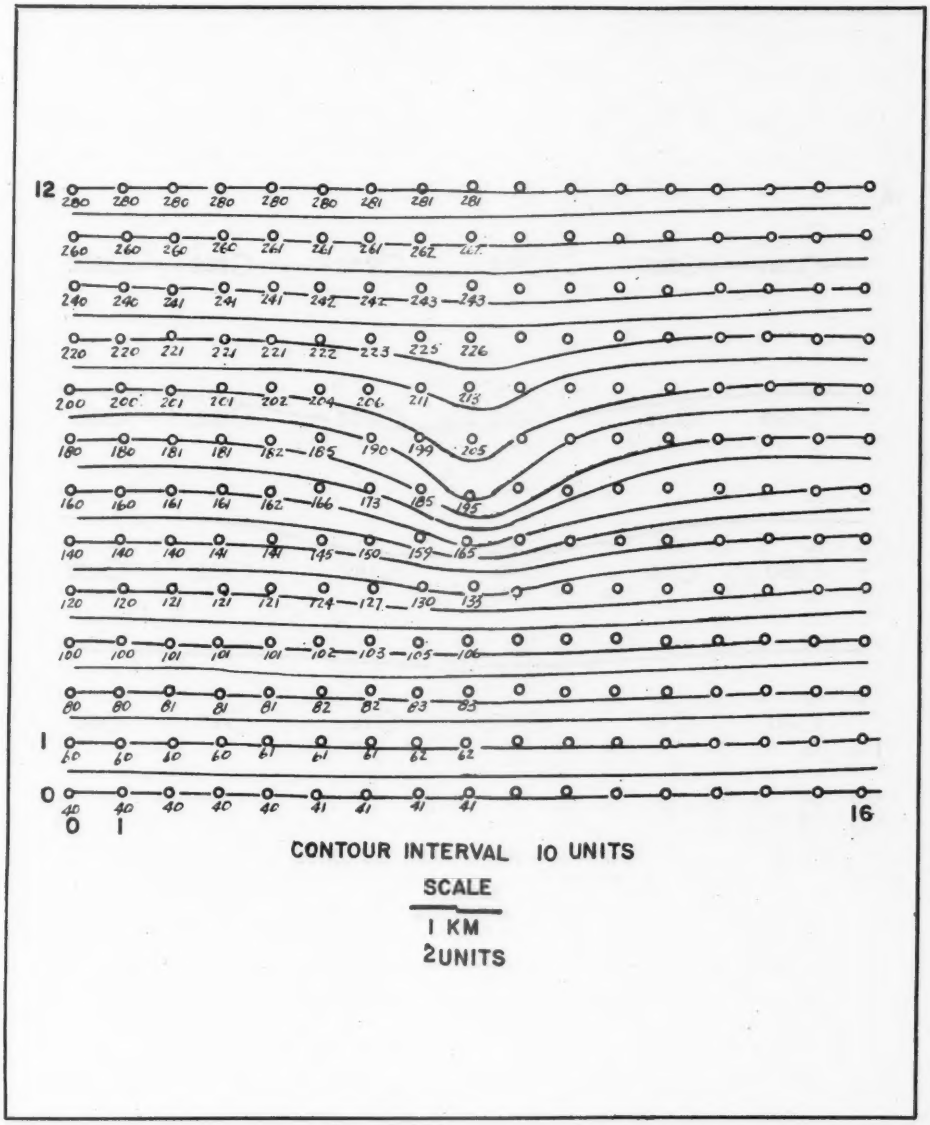

FIG. 1. The combined field of a buried sphere and a south gradient of 40 gravity units per kilometer.

method of *arithmetic means*. This method is illustrative of the interdependence between the chosen aerial distribution of control and the residual deviation. If the area of control points chosen is small, the regional value approaches the observed value, and the residual anomaly approaches zero, and if the area of control is chosen extremely large, the regional approaches zero, and the residual value approaches the observed anomaly value. Hence, in this method it is neces-

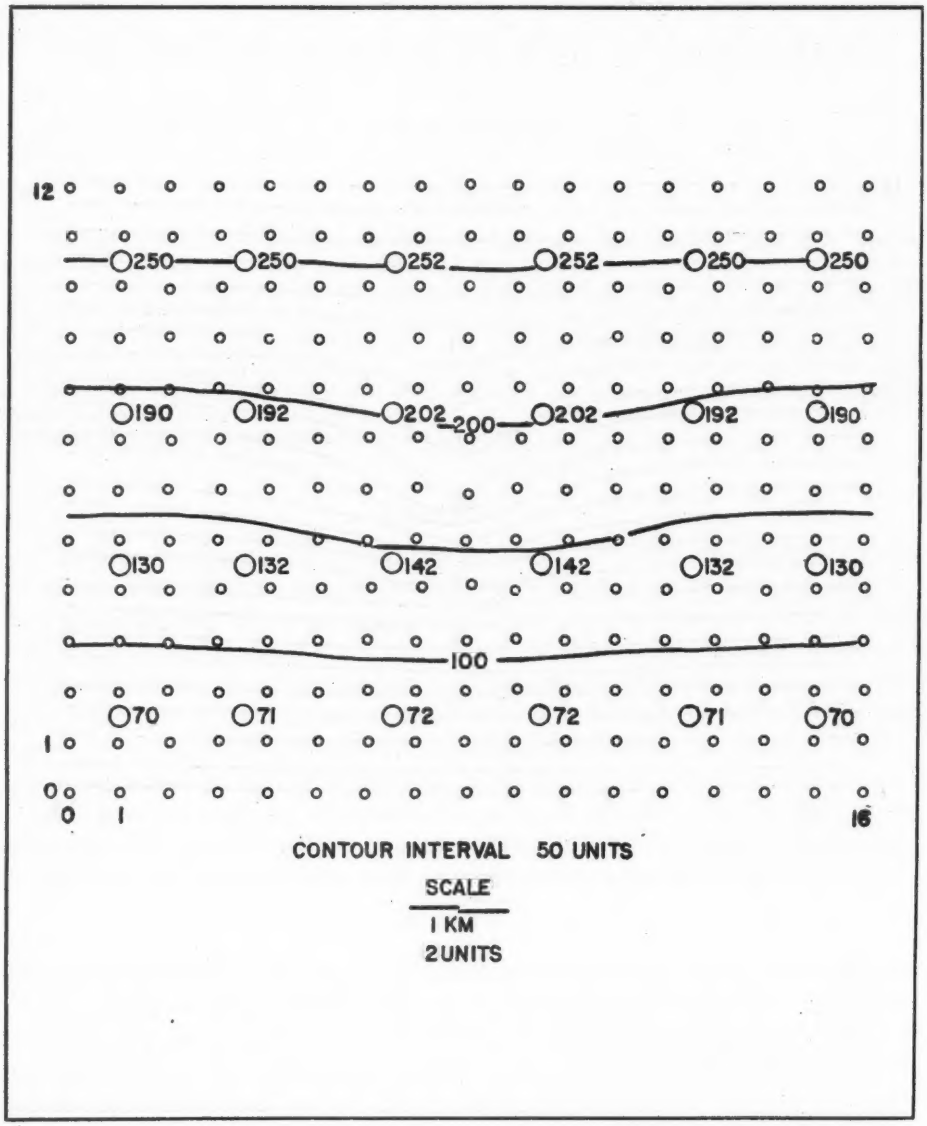

FIG. 2. The regional determined by the arithmetic mean, using the data shown in Figure 1.

sary to choose an area intermediate between the two extremes which will limit the effect of the regional elements but will show the residual with the least distortion.

The value of the arithmetic mean for the regional is placed in the center of the area of control, and these mean values or regional values are contoured. The contoured results of these mean values is the chosen regional.

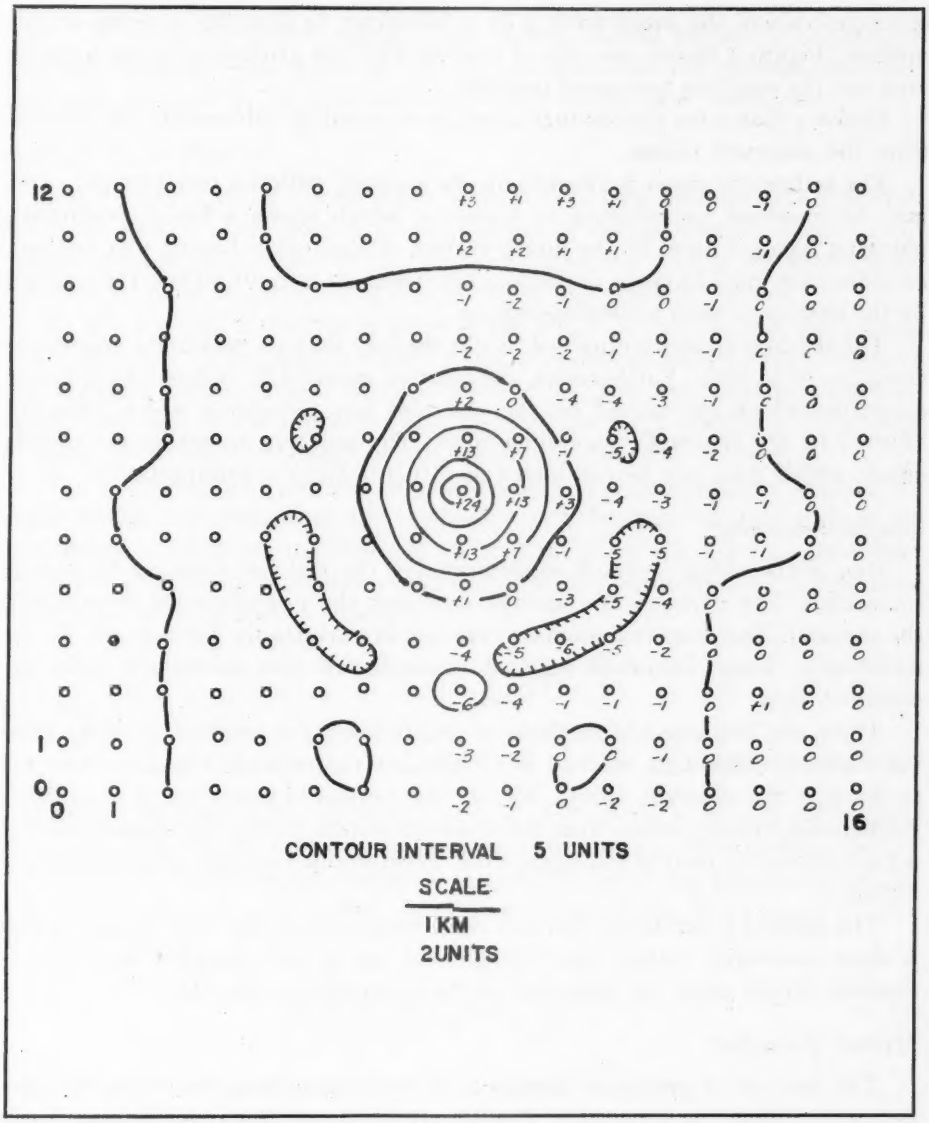

FIG. 3. The residual anomaly using the arithmetic mean regional.

The data shown in Figure 1 were used to illustrate the method. Figure 1 shows the field due to a spherical mass of density contrast unity on which is superimposed a south regional of 40 units per kilometer. The depth to the center of mass of the disturbing mass is 1,000 meters, and its radius is 500 meters. The maximum deviation due to the anomalous mass is 34.8 gravity units.

An area of 1.5 kilometers square was chosen, with the exception of the edges

of control where the areas are 1.5 by 1 kilometer to illustrate the use of this method. Figure 2 shows the area of control with the arithmetic mean for each area and the resulting contoured regional.

Figure 3 illustrates the residual anomaly obtained by subtracting the regional from the observed values.

The arithmetic mean is affected by the anomaly which is being sought. This may be observed by referring to Figure 2, which shows a broad, southward plunging regional nose. In the interpretation of the regional using this method, consideration must be given to the possible distortion introduced into the regional by the shallow or local anomalous effects.

The residual anomaly obtained by the method shows a maximum anomalous deviation of 30 units. Furthermore, the positive anomaly is "haloed" by negative anomalies which are caused by the observed low reentrants which were not affected by the regional's smoothing effect. The negative anomalies are pseudo effects which must not be considered as structural in the interpretation.

Contour Smoothing

One of the oldest methods of determining the residual anomaly is contour smoothing. The name of the method describes the procedure for determining the regional. The observed anomaly contours are arbitrarily "smoothed" by the interpreter. These smoothed regional contours are then subtracted from the observed data.

There are two possible methods of determining the residual anomaly from the observed data. One method is to subtract the regional contours from the contours of the observed values. The second method of procedure is to subtract the regional contour values from the observed station values. The former method is that commonly used in geological work to determine structure prior to regional tilting.

The method is similar to that described previously except that the smoothing is done arbitrarily rather than through the use of the observed data, and it depends mainly upon the judgment of the interpreter of the data.

Method of Profiles

The method of profiles is similar to contour smoothing, excepting the procedure for doing the smoothing. Profiles are drawn on the anomaly map in the direction of maximum gradients. The distance of separation of the control profiles is usually of the order of the width of the local anomalies. Along the length of the profiles a constant gradient is assumed. This constant gradient is taken as the regional gradient. Along zones of gradient changes in the observed data, the regional gradient is adjusted or changed along the profile.

The regional gradient as indicated along the profiles is contoured smoothly, and the resultant is the regional field.

The residual anomaly is obtained by subtracting the regional contour value

from the observed station values. With closely spaced profiles and averaged gradients approximately equal to the observed gradients the residual anomalies approach zero due to the elimination of all but sharp, local variations.

Average Profile Method

The area covered by the survey is broken into a grid by intersecting profiles, regularly spaced. The spacing of the profiles is chosen usually equal to the station spacing. The values at the intersections of the profiles are used for the calculation of the regional by interpolation of the observed values.

In this method, a running average of the values is carried, and the average value, which is the regional, is placed at the midpoint of the segment over which the averages were obtained. At each point of the grid, two average values are determined, one for the x direction and the other for the y direction. The average of these two average values gives the regional for the point of the grid.

The average profile method or grid method is a least squares solution for the regional. Assuming that the regional Z is a function of x or y, then the probability of obtaining the observed value at the point x, y is a maximum when $\sum_1^n R_n^2$ is a minimum. It follows that the necessary conditions for a minimum for an area of plane surface, where

$$R = G - (Ax + By + C)$$

are that

$$\sum R\partial R/\partial A = 0; \qquad \sum R\partial R/\partial B = 0; \qquad \sum R\partial R/\partial C = 0 \qquad (2)$$

since R is a function of the unknowns A, B, C. Equations (2) are the normalizing equations. For a station located at the intersection of a pair of profiles, and for symmetrically distributed stations on the profiles, with the coordinates of the point of intersection $x=0$ and $y=0$, the constants A and B are equal to zero, and the regional

$$Z = C = \left(\sum_1^n G_{n,\,x,y} \right) \Big/ n. \qquad (3)$$

The residual anomaly at the point of intersection would be

$$R = G - Z = G - \left(\sum_1^n G_{n,\,x,y} \right) \Big/ n. \qquad (4)$$

The average values $(\Sigma G_{n,\ x,\ y})/n$ are contoured, and the resultant is the regional surface. The residual may be determined by subtracting these regional values at the grid points as indicated by Equation (4), or by subtracting the regional at the points of observation.

The determination of the residual at the grid points gives a false indication of the density of control. Furthermore, the control of the regional will be de-

pendent on the control exercised by the original contours on interpolated values at grid points. The determination of the residual at station locations from observed values may be contoured on the basis of the observed data, and false anomalies will not be introduced.

Least Squares Determination

The best fitting regional to the observed data may be determined by least squares methods. The method is simplest to use when the observed gradient indicates a uniform plane, although it is possible to fit more complex functions to the observed field.

The procedure followed is similar to that outlined above in the section on average profile method. Assuming that a plane would best fit the data, the equation for the plane is

$$Z = Ax + By + C \tag{5}$$

where Z would be the computed value of the regional for the coordinates x, y. A, B, and C are constants which are to be determined.

The residual or the deviation would be

$$R = G - Z = G - (Ax + By + C). \tag{6}$$

The necessary conditions for the sum of the squares of the deviations or residuals to be a minimum are set forth in equation (2). These conditions may be shown to be the following in terms of the coordinates of the points of observation and the observational values

$$\begin{aligned} \textstyle\sum R\partial R/\partial A &= \textstyle\sum Ax^2 + \sum Bxy + \sum Cx - \sum Gx = 0, \\ \textstyle\sum R\partial R/\partial B &= \textstyle\sum Axy + \sum By^2 + \sum Cy - \sum Gy = 0, \\ \textstyle\sum R\,\partial R/\partial C &= \textstyle\sum Ax + \sum By + \sum C - \sum G = 0. \end{aligned} \tag{7}$$

Equations (7) gives us three independent equations in terms of the coordinates and the observed values to solve for the three unknowns A, B, and C.

The method may be illustrated by the use of the data shown in Figure 1. Only the observed data are used, and it is found that the following are the terms for the normalizing equations (7)

x	y	G	Gx	Gy	x^2	y^2	xy
1,768	1,326	35,962	287,670	277,632	19,448	11,050	10,608

For the above determinations 221 stations were used, and the 0, 0 coordinate is in the southwest corner of the area of control. A distance of 500 meters between stations was taken as a unit of distance. Substituting the above tabular values into the normalizing equations, the following are obtained

$$\begin{aligned} 19{,}448A + 10{,}608B + 1{,}768C &= 287{,}760, \\ 10{,}608A + 11{,}050B + 1{,}326C &= 277{,}632, \\ 1{,}768A + 1{,}326B + 221C &= 35{,}962. \end{aligned} \tag{8}$$

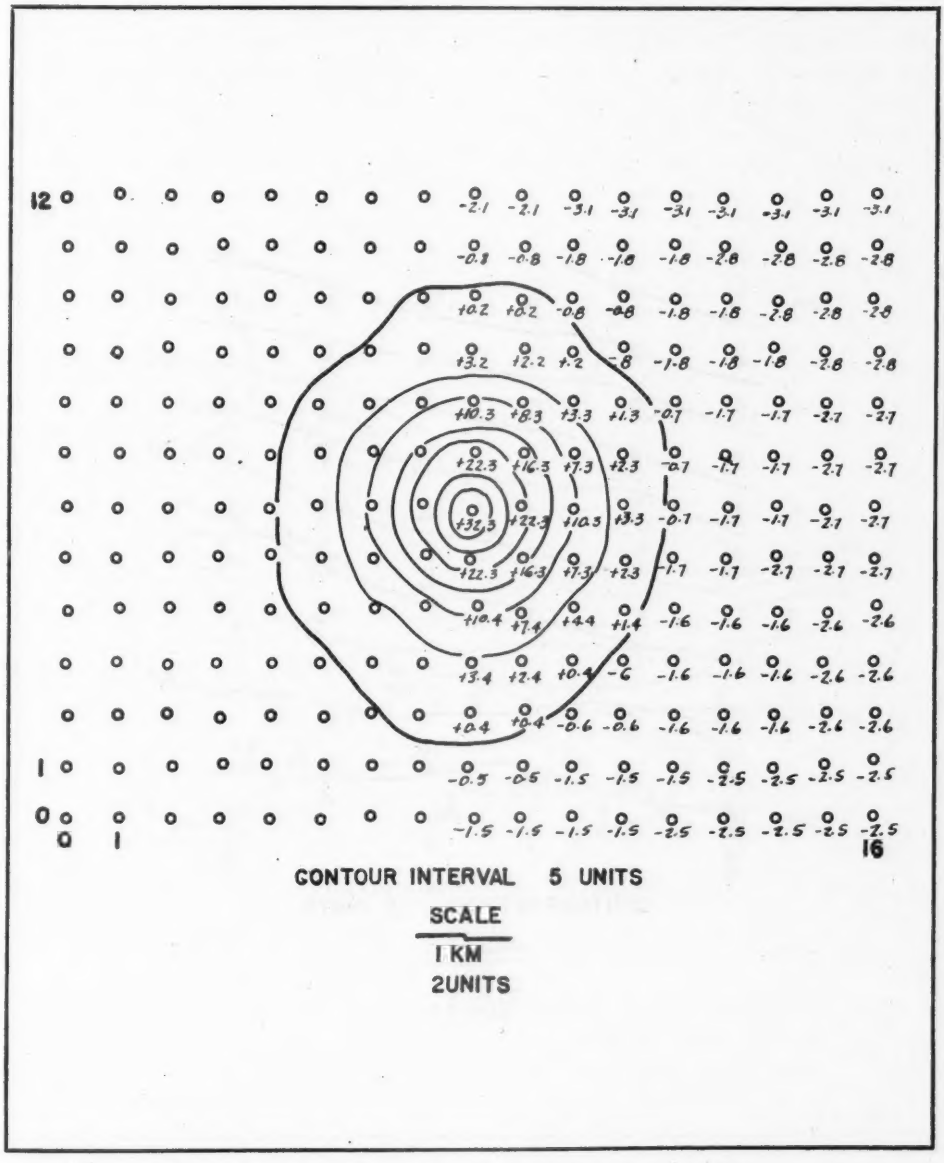

FIG. 4. Residual anomaly obtained by least squares fitting of data.

The solution of equations (8) yields the following for the regional

$$20.03y + 42.49 = Z. \tag{9}$$

The resultant residual anomaly is shown in Figure 4. It may be seen that the result of the inclusion of the anomaly is to raise the plane of the regional by two units above that of the true regional whose equation is

$$Z = 20y + 40$$

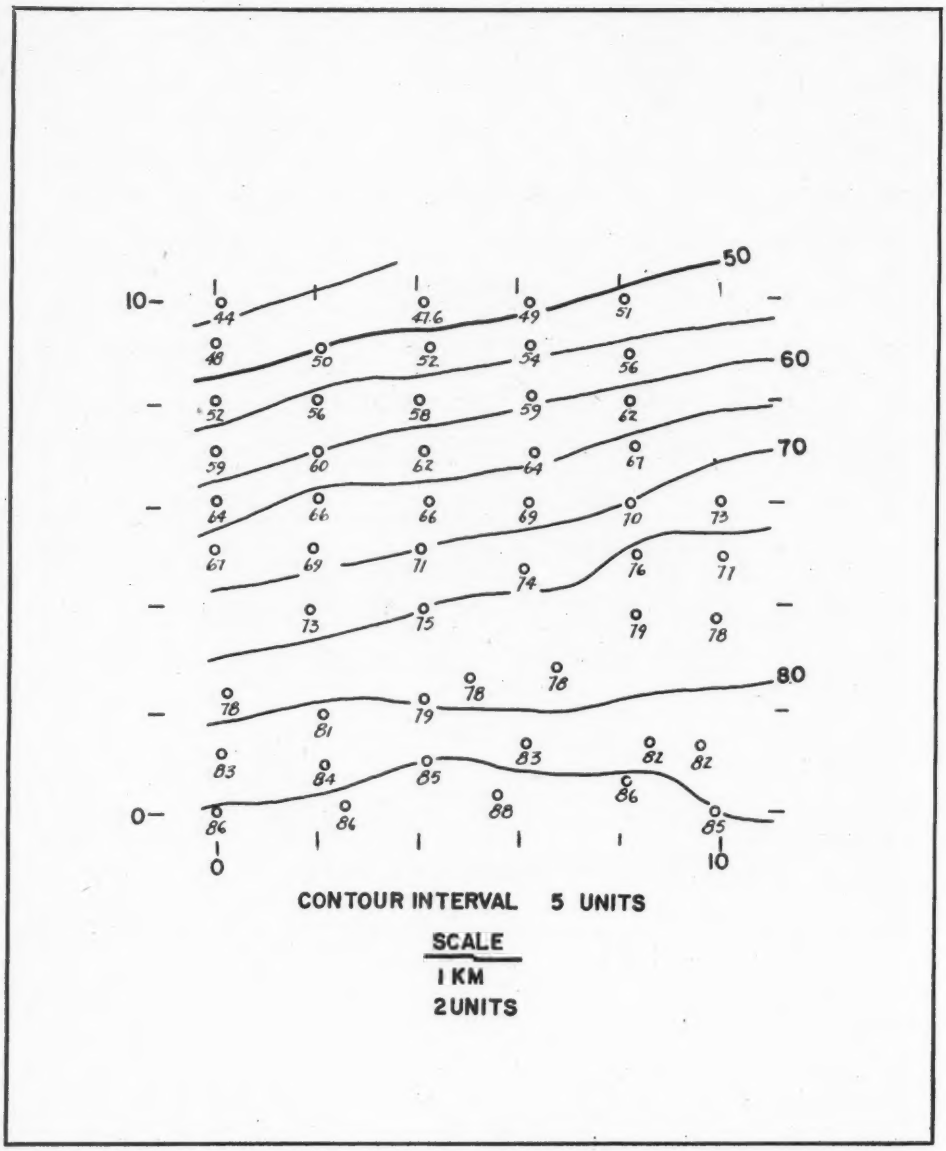

FIG. 5. Observed field data.

where Z is the regional and a unit distance is equal to 500 meters. The residual anomaly more nearly approximates the true anomaly, but this would be expected since the original anomaly was added to a plane regional.

Another set of data shown in Figure 5 has been used to determine the residual present. The equation of the regional here is found to be

$$Z = 0.36x - 5.04y + 93.5.$$

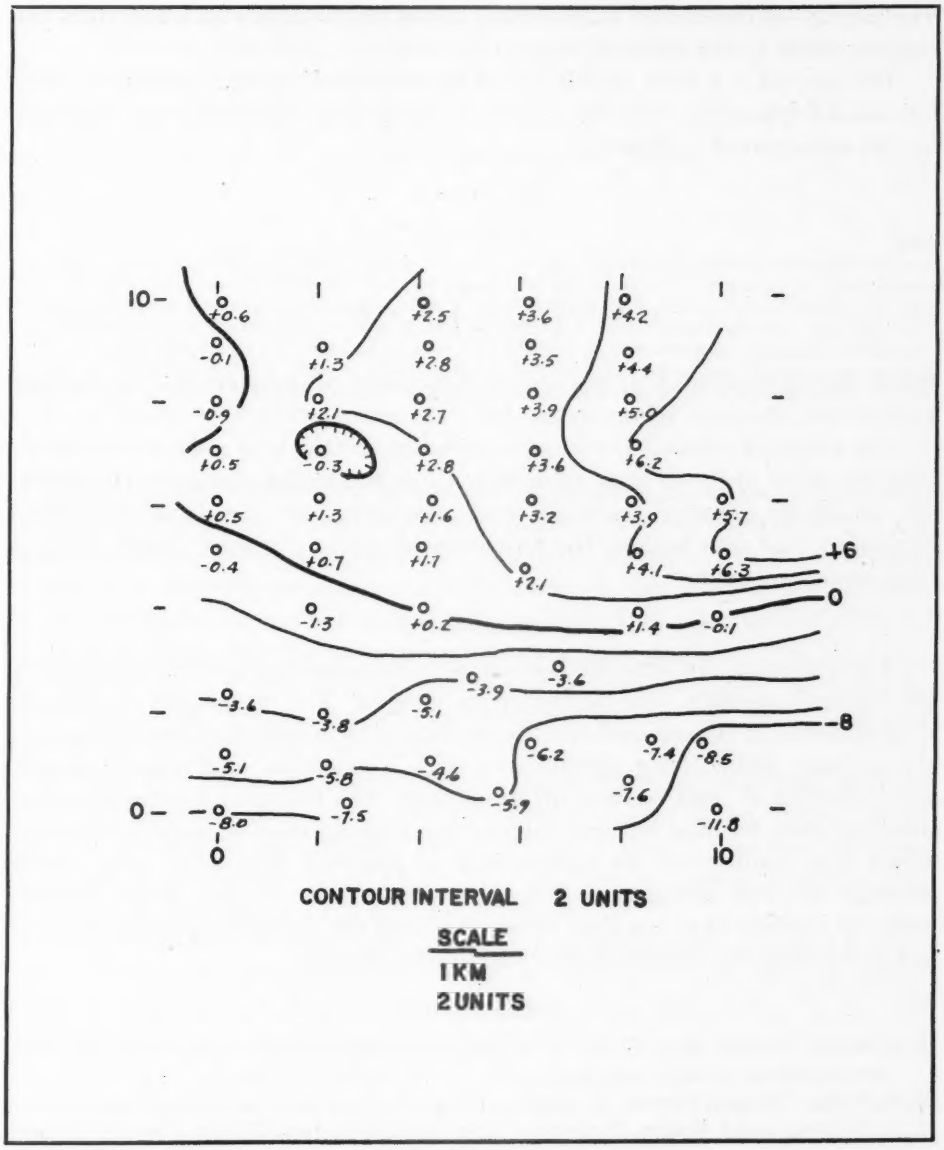

FIG. 6. Residual anomaly determined by least squares fitting of the observed data of Figure 5.

The resulting residual using the above equation for the regional is shown on Figure 6.

Circle or Polygon Summation

In circle or polygon summation, a template is made of arbitrary radius, and four, six, eight or ten points are placed at regular intervals around the circle.

The average of the sum of the observed values at the points on the circle is the regional value at the center of the circle.

The method is a least squares fit to the control of circular symmetry, since for circular symmetry, with the center of the circle as the origin, the constants for the equations of a plane are

$$A = B = 0$$

and

$$C = \left(\sum_{1}^{n} G_n \right) \Big/ n = Z.$$

Hence the regional value at the center of the circle of summation is the average value of the observed values on the circle of control.

The radius of control of the circle is chosen so that it is equal to or greater than the width of the average anomalies. Using this radius minimizes the formation of pseudo negative anomalies when averaging over the flanks of positive deviations, and also reduces the formation of rim or "haloing" highs about a true maximum point.

CONCLUSIONS

This paper has set forth the various methods commonly used for determining the regional anomaly, and therefrom the residual. The most rapid method for determination of the regional and the residual is by arithmetic means. However, the average profile, least squares and circle summation or polygon methods are variations of least squares fitting of data. The fitting of a regional to the observed data by least squares reduces the determination of pseudo anomalies which may result from the interpolation of observed data when using profile averages or circle summation. The study of the observed data in conjunction with the regional that has been determined and the residual determination will aid in deciding the validity of structural interpretations.

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THE WORLD-WIDE GRAVITY PROGRAM OF THE MAPPING AND CHARTING RESEARCH LABORATORY OF OHIO STATE UNIVERSITY*

W. HEISKANEN†

ABSTRACT

This paper deals with the geodetic applications of the gravity method. Gravity anomalies permit the *absolute* undulations of the geoid and the *absolute* deflections of the vertical to be determined. In turn, these, together with astronomical observations, form the basis for a World Geodetic System for the control of small scale maps beginning with the scale 1:100,000. They serve also, together with existing triangulations, for the correction of the dimensions of the reference ellipsoid. Additional gravity surveys are needed in order to obtain these and other minor objectives. Cooperation among scientists and agencies of different countries concerned with these problems is a prerequisite for the success of this world-wide program.

Gravity measurements can be used for geophysical, geological, prospecting, and geodetic purposes. Thousands of publications have been written about the geophysical and geological applications of gravity methods. The whole science of isostasy is essentially based on gravimetric studies. The famous strips of negative gravity anomalies in the East Indies, ir the West Indies, to the east of Japan, and west of South America have been discovered gravimetrically. The thickness of the first layers of the Earth's interior can be computed gravimetrically as well. The gravity method has been an important one for the oil industry and also for the mining industry in general.

When I was invited to Columbus last August, Professor Harding, Director of the Mapping and Charting Research Laboratory, asked me to study to what practical geodetic purposes gravity anomalies can be used. These investigations join closely to the studies which I have done with my co-workers in Finland for twenty years. The substance of all these studies is this:

The gravimetrist has only one tool, *gravity anomalies*, but this tool is very sharp. It can solve many problems, as follows. The gravity anomaly Δg is obtained in reducing the observed gravity value g to sea level, either by the aid of free air, Bouguer or isostatic reductions and subtracting from this reduced value g_0 the normal gravity value, γ, obtained from the gravity formula.

The *geophysical* basis of geodetic applications of the gravimetric method is the fact that all the quantities: the undulations of the geoid N, deflections of the vertical components ξ and η, and gravity anomalies Δg have the same cause, brought about by the same thing, the disturbing masses of the earth's interior. Δg can be observed, N, ξ, and η can be computed.

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The geodesist has the following difficulty. The geodetic measurements are reduced to an equipotential level, the *geoid*, and his astronomical observations are referred to the geoid as well; but he is compelled to carry out his geodetic computations along another more simple surface, the *ellipsoid of revolution* in order to get the coordinates of the control points. He must therefore have some method for converting the measurements from the geoid to the ellipsoid, i.e., for computing the quantities N, ξ and η. He has not had such a method so far.

As the classic arc measurements cover only a tiny part of the continents and they fail, at least up to now, totally in the oceans, the *arc measuring method* can give only the general *size* of the earth but not its exact *shape*. Only in some few parts of the world have the quantities N, ξ, and η been computed by means of this classic method, and even there the obtained values have not been correct.

The only method, which can give N, ξ, and η is the *gravimetric method*. In computing the undulations N of the geoid we need only to use the famous Stokes' formula, derived more than a century ago in 1849. The Stokes'-Vening Meinesz' formula (1928) gives the deflection of the vertical components ξ_g and η_g (we sign them now with the subindex g). These gravimetric quantities N, ξ_g, and η_g are *absolute* ones. They indicate the real undulations of the geoid and real angle (deflection of the vertical) between the normal of the ellipsoid used and the plumb-line.

What is needed is a fairly detailed gravity anomaly map of the vicinity of the points where it is desired to compute the quantities N, ξ_g, and η_g. In addition we need the general gravity anomaly maps over the world, which give the gravity anomalies in broad lines. As exploration geophysicists know, there are large areas in the United States, Canada, Europe, India, and small regions in many countries of the Middle East and Central and South America where detailed gravity anomaly maps exist.

In spite of the existing millions of gravity measurements in the world, however, we need for our purposes more *local* gravity surveys in many places as well as regional gravity measurements in some continents and oceans. If such new gravity measurements were to be carried out at nearly equal distance from one another, about 3,000 to 4,000 stations could give the *general* gravity field fairly well.

As to the *local* gravity field, about 100 gravity stations are needed inside the circle of 200 km radius in the vicinity of each deflection of vertical station. If more gravity data than this are available we, of course, use them all.

Under these conditions we can—omitting some minor results—obtain the following four objectives:

1. That of computing the undulations N of the geoid with an accuracy of 2 to 5 and the deflection of the vertical components ξ_g and η_g with an accuracy of 0.7″ to 1.0″. This can be done, e.g., at the initial points of the existing many different geodetic systems (North American, South American, European, Indian systems, etc.). In this way we can *convert* all these

systems to the same World Geodetic System. We have only to tilt and either uplift or lower each of these systems so much as the quantities ξ_g, η_g and N indicate.

2. That of converting the astronomical coordinates and azimuth from the geoid to the reference ellipsoid when we know the quantities ξ_g and η_g at the astronomical points. That will be accomplished by means of the equations:

$$\Phi = \Phi' - \xi_g$$
$$\lambda = \lambda' - \eta_g \sec \Phi$$
$$A = A' - \eta_g \tan \Phi$$

where Φ', λ', A' are the astronomical latitude, longitude, and azimuth referred to the geoid, and where Φ, λ, A are the corresponding geodetic quantities referred to the reference ellipsoid. Thereby we would establish the geodetic coordinates of all astronomic points in the World Geodetic System and, incidentally, the distance between any such points along the ellipsoid used, if necessary.

These distances can be easily converted from the ellipsoid to the geoidal distances. The point error will be about 1.0″ to 1.5″ or 30 to 45 m, and the error of the distance $\sqrt{2}$ times larger, or about 45 to 65 m.

3. That of controlling maps of scale 1:100,000 and maps of even smaller scale without any triangulation. This accuracy will not decrease with the distance, as is the case in the triangulation. The point accuracy noted in the second objective of 30 to 45 m corresponds to an accuracy of 0.3 to 0.45 mm on 1:100,000 scale maps and to an even smaller amount on maps of smaller scale.

4. That of correcting the dimensions of the used reference ellipsoid (as Lambert in 1947 pointed out) when comparing the gravimetrically computed quantities ξ_g and η_g at the astronomical points of the existing arc measurings with the corresponding quantities ξ and η obtained from the arc measurings.

If the differences $(\xi_g - \xi)$ and $(\eta_g - \eta)$ are small along the whole arc, the ellipsoid used is good, but if $(\xi_g - \xi)$ and $(\eta_g - \eta)$ increase or decrease systematically along the arc, we must correct the ellipsoid so that the systematical part of $(\xi_g - \xi)$ and $(\eta_g - \eta)$ disappears.

In collecting the existing gravity material and in analyzing them, such famous scientists as Vening Meinesz, Lejay, de Graaff Hunter, Hirvonen, Hess, Ewing, and Woollard have promised their wholehearted cooperation. Ewing's student, Dr. Worzel, will continue the world-wide gravity measurements at sea, and Woollard and his students will continue the global gravity measuring trips to the different continents and to the ocean islands. The "grand old man" of American geodesy, W. D. Lambert, is now a consultant of Ohio State University Laboratory. I myself will conduct the analyzing work.

Vening Meinesz, president of the International Union of Geodesy and Geophysics, has promised all possible help also from this Union.

We wish to get help for the "Columbus team." When we shortly will send members of the Society of Exploration Geophysicists a circular asking for gravity data, or still better, for gravity anomaly maps, I hope that members will be willing to let us have such gravity data. The laboratory doesn't need the exceptional values but only the mean values of squares, say of 50 to 100 square miles. All data will, of course, be used confidentially.

If gravity data contributed are not referred to sea level and are not tied to the general gravity systems, the "Madison team" of Professor Woollard will be ready to carry out necessary connection measurements. The world-wide gravity measuring trips of Woollard and of his students have basic significance for all geodetic application of the gravity measurements. Only by means of such world measuring trips can we reduce gravity values of different countries to the same system.

If it be presumed that necessary financial support will be available in addition to cooperation among the agencies and scientists concerned, the "Columbus team" will be able to accomplish the aims outlined here in the next three years. The geodetic problems involved are perhaps the most important in this century.

The International Union of Geodesy and Geophysics at its Ninth Congress (August 21 to September 1, 1951 at Brussels) adopted the following resolution concerning this world-wide program:

The International Union of Geodesy and Geophysics, considering

(a) that a more and more precise determination of the size and shape of the Earth and the fixing of positions on the same reference system constitutes one of the essential aims of the Association,

(b) and that, in spite of the gaps which exist in the world gravity system, a better knowledge of the size and shape of the Earth could be attained by the use of existing gravity data in association with existing triangulation,

(c) and that some indication might also be obtained concerning the differences between various systems of reference,

records

with great satisfaction the establishment of the large program of research by the *Mapping and Charting Research Laboratory of the Ohio State University of Columbus* (Ohio) and strongly approves its objectives,

and considers

it necessary that, in order to make this program conform with the aims of the Association close collaboration should be established with appropriate persons and institutions in order to study (a) gravity values, (b) such methods of reduction, and (c) such methods of calculation as will insure the greatest possible accuracy of the results and allow new gravity data to be used for future revision and extension.

PATENTS

O. F. RITZMANN*

GEOCHEMICAL PROSPECTING

U. S. No. 2,551,449. J. R. Menke. Iss. 5/1/51. App. 6/15/49. Assign. Nuclear Development Associates, Inc.

Method for Locating Deposits. A geochemical-prospecting system in which samples are analyzed for an indicative element and the relative abundance of its isotopes measured and plotted.

MAGNETIC PROSPECTING

U. S. No. 2,549,845. J. C. Mouzon, E. S. Lamar and J. Bardeen. Iss. 4/24/51. App. 6/26/45.

Ship's Magnetic Submarine Detector. A submarine-detecting system for a ship having oppositely-connected detecting coils located fore and aft normal to the longitudinal axis of the ship, and compensating coils perpendicular to the detecting coils and to each other in series with the detecting coils.

U. S. No. 2,549,857. E. O. Schonstedt. Iss. 4/24/51. App. 6/27/46.

Cable-Suspended Aerodynamic Body. A bird for housing an airborne magnetometer in which the magnetometer head may be rotated 90° about a longitudinal axis and the center of suspension maintained above the center of gravity to maintain stability in flight.

U. S. No. 2,550,719. R. Raspet. Iss. 5/1/51. App. 10/14/47.

Temperature Compensation Means for Magnetic Field Balances. A magnetic field balance whose moving system has adjustable masses on threaded arms extending perpendicular to the magnet axis, the rods being made of dissimilar metals to shift the mass in a direction parallel to the magnet axis with temperature changes.

U. S. No. 2,551,596. G. O. Haglund. Iss. 5/8/51. App. 5/21/46.

Aerodynamic Body for Carrying Detection Apparatus. A bird for housing an airborne magnetometer to which the towing cable is attached through gimbals located at the cross-sectional center of form and above the center of gravity.

U. S. No. 2,555,209. V. V. Vacquier and G. Muffly. Iss. 5/29/51. App. 11/1/43. Assign. Gulf Research & Development Co.

Method and Apparatus for Measuring the Values of Magnetic Fields. A gimbal-mounted aircraft magnetometer stabilized in two planes with the stabilizations controlled by one or more magnetically-sensitive devices.

U. S. No. 2,556,199. F. W. Lee. Iss. 6/12/51. App. 12/31/47.

Dynamically Balanced Weight System. A magnetic field balance which is mounted on gimbals maintained horizontal by a pendulum and having compensating magnets in the pendulum and also in horizontal arms.

SEISMIC PROSPECTING

U. S. No. 2,547,703. A. J. Hermont and J. C. Toups. Iss. 4/3/51. App. 7/10/48. Assign. Shell Development Co.

Seismic Exploration System. A seismograph avc system having a multi-stage signal transmission channel with nonlinear resistances in a bridge circuit to control the input of each stage, and a control-signal channel with rectifiers to supply bias current to the bridges.

* Gulf Oil Corporation, Patent Department.

U. S. No. 2,548,990. K. W. McLoad. Iss. 4/17/51. App. 10/5/48. Assign. Socony-Vacuum Oil Co., Inc.

Invertible Geophone. A geophone in which the parts whose relative motion is detected are independently suspended from the case and arranged so that gravity causes one of them to rest against a stop when the geophone is in one position and the other one to rest against a stop when the geophone is in an inverted position.

U. S. No. 2,551,417. C. H. Carlisle. Iss. 5/1/51. App. 6/27/46. Assign. Standard Oil Development Co.

Apparatus for Seismic Exploration. A cable and detector assembly for under-water seismic operations having a relatively rigid cable onto which two similar halves of a geophone case may be clamped and with the geophone system rotatively mounted in the case with its center of gravity off the axis so that the geophone system always remains right side up.

U. S. No. 2,551,857. A. N. Stanton. Iss. 5/8/51. App. 9/6/49.

Vertical-Vibration Pickup. An electromagnetic geophone having a horizontal cylindrical case with the cable passing through a hole on its axis and an annular magnet with suspended moving coil which is made to move by an annular mass on a tube with an annular plate whose lower edge engages the coil so that the device will operate in any angular position about a horizontal axis.

U. S. No. 2,554,905. J. E. Hawkins and J. R. Cornett. Iss. 5/29/51. App. 6/1/46. Assign. Seismograph Service Corp.

Seismic Signal Amplifier. A seismograph avc system having two cascaded attenuator networks each with variable impedance rectifiers whose bias is obtained from the amplifier output.

U. S. No. 2,555,806. G. D. Mitchell, Jr. Iss. 6/5/51. App. 3/18/47. Assign. Texaco Development Corp.

Seismic Prospecting Method, Including Generation of a Cylindrical Wave Front. A method of seismic prospecting in which a number of shots along a line parallel to the line of geophones are fired simultaneously so as to generate a cylindrical wave front which arrives at all of the geophones at the same time.

U. S. No. 2,556,299. C. B. Scott. Iss. 6/12/51. App. 9/12/47. Assign. Standard Oil Development Co.

Method of Generating Directional Seismic Waves. A method of seismic shooting in which a vertical distribution of explosive is placed in a shot hole and detonated at the top, the explosive having a detonation rate equal to the seismic velocity in the earth adjacent the shot hole as determined by a trial shot.

U. S. No. 2,557,714. P. S. Williams. Iss. 6/19/51. App. 9/13/47. Assign. Standard Oil Development Co.

Shot Pulse Recording in Reflection Seismography. A method for improving the identification of reflections by recording the incident impulse with a geophone placed in a borehole in the path of the incident energy and connected to an amplifier whose attenuation function is the same as that of the earth.

U. S. No. 2,557,888. R. W. Olson. Iss. 6/19/51. App. 3/7/49. Assign. Geophysical Service, Inc.

Attenuating Circuit. An avc circuit for a push-pull amplifier in which two resistors are connected in series with the grid of each amplifying tube and the points between the resistors returned to ground through opposed diodes which are biased by the control voltage.

WELL LOGGING

U. S. No. 2,547,875. S. Krasnow. Iss. 4/3/51. App. 10/29/36. Assign. Schlumberger Well Surveying Corp.

Apparatus for Taking Physical Measurements in Boreholes. A system for remotely indicating a

well-logging parameter in which the parameter is made to change the current in a saturable reactor in an oscillator circuit in the well so as to change its frequency, and the oscillator output is converted to acoustic vibration of a wire line for transmitting up the hole and indicated by a vibration detector in contact with the line at the surface.

U. S. No. 2,547,876. S. Krasnow. Iss. 4/3/51. App. 1/5/44. Assign. Schlumberger Well Surveying Corp.

Apparatus for Investigating a Plurality of Physical Values in Boreholes. A system for remotely indicating two well-logging parameters in which one parameter is made to change the frequency of an oscillator in the well by changing the current through a saturable reactor in its circuit and the other parameter controls the frequency of a second oscillator in the well which modulates the signal of the first, the combined signal being impressed on the wire line as an acoustic vibration which is picked up at the surface and separated into the two components.

U. S. No. 2,547,950. B. D. Lee and G. Herzog. Iss. 4/10/51. App. 5/14/49. Assign. The Texas Co.

Electrical Analogue. An electrical model for electric well logging having a wedge-shaped tank of electrolyte with a partition parallel to the sharp edge of the wedge, the partition being made of insulating material with conducting inserts so that current can flow through the partition but not along it.

U. S. No. 2,549,109. J. W. McPhee. Iss. 4/17/51. App. 3/19/49. Assign. Lane-Wells Co.

Radioactive Locating Means. A method of radioactive depth marking by using a casing collar having a radioactive material homogeneously incorporated in it.

U. S. No. 2,550,004. H-G. Doll. Iss. 4/24/51. App. 12/22/43. Assign. Schlumberger Well Surveying Corp.

Method of Establishing Markers in Boreholes. A method of producing a depth marker inside casing which is related to a radioactive marker outside the casing by running a radioactivity detector and an adjacent electrode and passing a large current into the casing from the electrode so as to polarize the casing, the polarization being subsequently located with a natural potential log.

U. S. No. 2,550,005. H-G. Doll. Iss. 4/24/51. App. 4/22/48. Assign. Schlumberger Well Surveying Corp.

Well Logging Method and Apparatus Utilizing Periodically Variable Spontaneous Potentials. A system for producing fluctuating pressure in a fluid-filled well by means of a reciprocating pump piston and observing the alternating electro-filtration potential produced at various horizons.

U. S. No. 2,552,428. A. B. Hildebrandt. Iss. 5/8/51. App. 9/21/49. Assign. Standard Oil Development Co.

Sleeve Supported Electrode for Well Logging. An electric-logging electrode system having a spring-expanded sleeve of electrically-insulating material carrying on its outer surface electrodes which are pressed against the formation but which are insulated from the body of drilling fluid in the borehole.

U. S. No. 2,553,235. A. Blanchard. Iss. 5/15/51. App. 2/17/45. Assign. Schlumberger Well Surveying Corp.

Method for Determining the Presence of Gas in Dispersions. A method of determining gas in drilling mud by subjecting the mud to supersonic vibration and measuring the potential developed between a pair of electrodes immersed in the mud.

U. S. No. 2,553,350. J. F. Bayhi. Iss. 5/15/51. App. 4/17/47. Assign. Standard Oil Development Co.

Method and Apparatus for Detecting Corrosion. A system for detecting corrosion of pipe caused by electrolysis which has a magnet rotating in a horizontal plane close to the inside surface of the pipe and also has longitudinally-spaced electrodes which contact the pipe and separately recording variations in magnetic flux and potential with depth.

U. S. No. 2,554,174. H-G. Doll. Iss. 5/22/51. App. 6/13/42 and 10/8/47. Assign. Schlumberger Well Surveying Corp.

Well Logging Method and Apparatus. A system for determining permeability of formations by forcing fluid alternately against one side of the hole and the other and measuring the alternating differential electrofiltration potential developed between electrodes on each side of the apparatus.

U. S. No. 2,554,844. L. M. Swift. Iss. 5/29/51. App. 3/22/46. Assign. Well Surveys, Inc.

Casing Collar Locator. A well-logging sonde having a non-magnetic section in its case with magnet pole pieces above and below it and a coil for detecting variations in flux caused by casing collars in an electronic circuit for superimposing the collar signals on the logging signal.

U. S. No. 2,557,168. J. J. Arps and O. W. Ward. Iss. 6/19/51. App. 11/28/49.

Continuous Electric Logging While Drilling. A method of electric logging while drilling in which a relaxation oscillator in the drill is connected to insulated electrodes and each oscillation trips a relay which disconnects an insulated section of the drill string, the change of resistance of the drill string to ground being detected at the surface.

U. S. No. 2,557,488. C. L. White. Iss. 6/19/51. App. 3/28/47. Assign. Phillips Petroleum Co.

Apparatus for and Method of Determining Permeability of Earth Formations Penetrated by Well Bores. A method of determining permeability by placing a liquid opposite the formation and a lighter liquid above it and following the interface down the well by means of a line and float of intermediate density which floats on the interface.

U. S. No. 2,558,427. H. C. Fagan. Iss. 6/26/51. App. 5/8/46. Assign. Schlumberger Well Surveying Corp.

Casing Collar Locator. A magnetic differential type casing joint locator having two permanent magnet circuits each including part of the casing so as to form a magnetic bridge with a pick-up coil between the magnets to detect unbalance caused by the joint.

MISCELLANEOUS

U. S. No. 2,552,890. J. D. Eisler. Iss. 5/15/51. App. 3/9/44. Assign. Stanolind Oil and Gas Co.

Elevation Indicator. An elevation meter for use on a vehicle having a disc pendulum carried on a transverse horizontal axis by torsion elements and reflecting a beam of light to a photocell after reflection at an angle proportional to the pendulum deflection.

U. S. No. 2,557,021. P. S. Williams. Iss. 6/12/51. App. 9/12/46. Assign. Standard Oil Development Co.

Hydraulic System for Measuring Differences in Elevation. An elevation measuring system in which the points are connected by a liquid-filled tube and difference in pressure observed.

U. S. No. 2,557,158. C. F. Teichmann. Iss. 6/19/51. App. 11/30/48. Assign. Texaco Development Corp.

Radioactive Exploration. A system for radioactivity surveying from an aircraft in which a directional detector is adjusted by means of a cam to point toward a fixed spot on the ground as the craft flies over it and after completing the measurement is directed to a new spot.

U. S. No. 2,557,691. F. Rieber. Iss. 6/19/51. App. 3/19/49. Assign. Geovision Inc.

Electronic Function Generator. A system of portraying reflecting horizons on a c-r tube screen in which the velocity-depth function is introduced by having a photocell pick up light from an auxiliary c-r tube through an empirically-made absorption wedge and modulate the scanning of the portraying tube.

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Science and Common Sense, by James B. Conant, Yale University Press, New Haven, 1951, 371 pp., $4.00.

In this book, Dr. Conant, who is President of Harvard University as well as a distinguished organic chemist, has endeavored to explain the methods of experimental science for the layman. Drawing largely on material which he presented over a three-year period to Harvard undergraduates taking a survey course in Natural Science, he addresses this book to "the intelligent citizen who as a voter may, to an increasing extent, be interested in congressional action on scientific matters" as well as to "the lawyer, banker, industrialist, government official, politician or newspaperman." Although the author has intended it for those with little or no training in the sciences, the book should make worth while, stimulating reading for many actually engaged in scientific activity.

If everyone who refers at one time or another to the "scientific method," were pressed to define the term, there would probably be a wide range of variation in the replies. To some it is the organization and classification of information; to others it is the impartial and rational derivation of conclusions from facts. Still others would consider it the synthesis of many separate observations into a statement of ultimate reality. To Dr. Conant, the scientific method is something more specific; it is the formulation, as a result of experimentation and observation, of a conceptual scheme, such as a hypothesis or theory, which yields deductions that can be tested by further experiment and observation. All the other definitions are inadequate because they describe equally well many other spheres of activity, ranging from history to the detection of criminals which would not be classified as science. On the basis of Conant's definition, science is dynamic and requires continual progress from experi-

ment to deduction to experiment. If all laboratories were to close, science would cease to exist, no matter how great the accumulation of scientific information in the libraries. Science, in such an event, would turn into dogma.

The author's approach is essentially historical. He illustrates his explanations of the scientific method by fairly detailed accounts of classic experiments conducted by such pioneers in physics, chemistry and biology as Torricelli, Boyle, Lavoisier, Volta, and Pasteur. These examples are chosen for their simplicity since it is much easier to explain, in a book for the layman, the development of the concept that the atmosphere exerts a pressure than to present the origins of the quantum theory in a way that appeals to him.

A chapter on earth sciences entitled "The Study of the Past" points out the methods and ways of thinking which are peculiar to geology, also why geology is a science and why history is not although both aim to give us a record of the past. A brief section on geophysics emphasizes the point that there is little difference between the methods of geophysics and the methods of physics.

In discussing gravity measurements in this section, the author falls into the error of referring to "variations in the gravitational constant" from place to place. In a brief reference to seismic prospecting he indicates that "formations" associated with petroleum can be located by observing the speed of seismic waves through them. "Structures" would be a more accurate term. Both slips are minor and do not detract in the least from the validity of the discussion on the geologic sciences.

The most interesting chapter to most readers engaged in commercial geophysics should be the one entitled "The Impact of Science on Industry and Medicine." Here he makes the highly cogent point that the chief object of industrial research should be to reduce the degree of empiricism in the processes involved. The less empiricism required, the better is the conceptual structure by which predictions can be made and new applications can be deduced. The analysis here reminds the reviewer of Paul Weaver's stimulating essay, "The Relative Place of Empirical and Analytical Methods of Geophysical Prospecting," published in *Geophysics* in July, 1942. This broader view of the purpose of applied research will probably not be accepted by many executives who look for more tangible products or improvements to justify research expenditures. But in the long run, reduction of empiricism usually pays off better than the type of "research" program which is limited to more immediate practical objectives.

Dr. Conant's book is recommended to all readers of this journal as a lucid and thought-provoking discussion of a subject that concerns all geophysicists, both professionally and as citizens who must help establish public policy regarding the place of science in our national life.

MILTON B. DOBRIN

"Die geophysikalische Erschliebung des Emslandes," by Dr. Hans Cloos. *Erdöl und Kohle*, Hamburg, Germany, No. 5, Vol. 4, May, 1951.

This article is an excellent case history describing the discovery of oil in this area and includes a discussion of the economic, geologic, geophysical, and, to a limited extent, philosophical factors. Its organization is patterned very closely to many of the case histories appearing in the Society's *Geophysical Case Histories* volume, which the author states in the introduction is his intent. The seventeen illustrations are an important factor in aiding the reader in following the detailed geologic interpretation of the reflection and refraction seismic as well as the magnetic and gravity data because these are discussed more thoroughly, particularly from the stratigraphic and paleogeographic aspects, than in the average case history. Dr. Cloos also presents from an historical standpoint the discovery and development of this area in which there was no commercial interest prior to 1938; perhaps because there was no subsurface information. However, the original refraction work, which did not succeed in outlining any commercial structures, served to arouse interest in the area, and several reflection seismic surveys and a more detailed gravity survey were subsequently conducted.

The early regional magnetic and gravity surveys were not adequate to be of commercial significance. However, academically they furnished a picture which could be used as a basis of discussion regarding the basement configuration and variation in thickness of the sediments. A more detailed commercial gravity survey that was conducted subsequently showed the presence of small anomalies superimposed on the regional effects. The small amount of torsion balance data available is also dis-

cussed and the conclusion drawn that it was of no commercial value except for outlining a few special trends.

A tribute to the quality of American geophysical instruments is made in this paper because of its statement that when no significant seismic reflection data were obtained in the early 1940's it was hoped when American equipment became available that the area could be worked successfully. However, when this equipment became available, although improved results were obtained, superior interpretation techniques were necessary to utilize the new records to the best advantage.

The general impressions obtained from reading this article are that geophysics and geology have no political boundaries, that comparable problems occur on a global scale, and that the techniques which can be used to solve a certain geological-geophysical situation in one area will be equally successful in another provided similar factors are involved; also that the more subsurface geologic information available, the better will be the resulting interpretation of the geophysical information.

RICHARD A. GEYER

Practical Oil Geology (6th ed.), by Dorsey Hager, McGraw-Hill Book Co., Inc., New York, 1951, 589 pp., $7.50.

Dorsey Hager has revised his comprehensive volume on the relationship of geological work and the oil industry. In it there is a great deal of material which is reminiscent of Lahee's classic volume on field geology. However, Hager deals more extensively with petroleum exploration, the drilling of wells, and the work of the petroleum geologist.

As a handbook for the practicing petroleum geologist, its value is limited. It would serve very well for students as an introduction to petroleum geology, and for those whose work necessitates an understanding of petroleum geology in all its many phases.

ROBERT W. GARWICK
General Crude Oil Company

Physical Geography, by Arthur N. Strahler, John Wiley and Sons, New York, 1951, 442 pp. (double columns), $6.00.

Principles of Human Geography, 6th edition, by Ellsworth Huntington, revised by Earl B. Shaw, John Wiley and Sons, New York, 1951, 773 pp., $6.25.

Both of these books present geography in a somewhat different light from that in which many of us, whose last formal contact with it was in grade school, tend to regard the subject. Neither makes any effort, except for purposes of illustration, to catalog information on the natural or cultural features of specific localities. Both are more concerned with the general principles governing the various kinds of environment in which man lives. Professor Strahler's book treats the physical factors, such as climate and physiography, which control environment. The late Professor Huntington's book, on the other hand, deals with the dependence of human activity and development upon environment. Taken together, the two books cover both the cause and the effect of the environmental conditions found in areas of human habitation.

Physical Geography is an exceptionally attractive, well-written treatise on the physics of the earth's surface. It is intended for college students who have had little or no background in physical science or mathematics. As Professor Strahler points out in the introduction, physical geography is a body of basic principles selected from geodesy, astronomy, cartography, geomorphology, geology, hydrology, meteorology, botany, and oceanography. There are few persons, even among the technically trained, who are so familiar with all these branches of earth science that they cannot obtain a better understanding of many natural phenomena from an elementary, non-mathematical presentation such as this. Although most of the sciences from which physical geography is derived are divisions of geophysics, the average geophysicist, like most others in scientific work, will probably find much outside his particular specialty that is new to him in a book of this type.

Strahler's book is divided into three parts. The first deals with topics relating to the earth's shape and rotation, such as illumination, time, and tide. The second deals with maps, landforms, and

geologic structures affecting topography. The emphasis given this phase of the subject reflects the author's primary field of interest, which is geomorphology, and this section alone could constitute a good beginning text in this field. The third part covers weather, climate, vegetation, and soils. The photographs and line drawings are unusually numerous, well planned, and effectively reproduced. Full use is made of maps and block diagrams, particularly in the section dealing with geomorphology.

The Huntington book considers geography not so much a physical science as a social science although such topics as weather, climate, maps, and physiography are treated from the physical standpoint. The scope of the book can best be conveyed by listing the headings for its ten major divisions: Man's Geographical Relationship, Man's Relation to the Earth as a Globe, The Fundamentals of Climate, Man's Relation to Land Forms, Physiography and Human Progress, Man's Relation to Soil and Minerals, Man's Relation to Climate, Man's Regional Relationships, Man's Relation to Man, and Countries of the World. Emphasis is given throughout to the explanation of differences between various racial, national, and regional groups on the basis of geographic distinction. The last part of the book, Countries of the World, summarizes the histories of the various nations in terms of their individual geographic influences.

Although on the surface there might not appear to be any close connection between human geography and geophysical prospecting, there is actually an intimate relationship, especially as regards the planning of field operations. To plan a seismic or gravity survey in a new area requires knowledge of climatic factors, topography, transportational facilities, and local availability of food and fuel. While this book could not in itself serve as an adequate source of such information for all areas in which geophysical operations might be intended, it should focus attention on the many problems that inevitably arise in any activity where environment is as controlling a factor as it is in prospecting. The book contains a fairly complete bibliography, with titles arranged according to location, which should be useful when problems arise in specific areas.

MILTON B. DOBRIN

Geography of the Pacific, edited by Otis W. Freeman, John Wiley & Sons, New York, 1951, 573 pp.

If anyone wishes to know the elevation and the square area of certain Pacific islands, or other types of factual data on population, commerce, and climate, this book is recommended highly for these purposes. In short, it is a compendium of facts, figures, photographs and maps written by thirteen specialists and is suitable as a reference book for all age groups from junior high school through college and adult education. However, it is not a mature "geography book" from the standpoint of discussing and integrating the complex inter-relationships among the physical, human, commercial, and political factors which comprise the mature approach to a study of geography and geopolitics. This fact was particularly apparent to the reviewer because of having recently reviewed such a "geography book," *Geography in the Twentieth Century*, in the July 1951 issue of *Geophysics*.

Admittedly, it is difficult to have continuity or a general theme in a book written by a dozen or more people; nevertheless, absence of such does not facilitate the reading of this book from cover to cover. In addition, all the contributors are from the United States, and the areas involved include countries which have their own competent geographers whose contributions might have resulted in achieving a more international and authoritative quality. The criterion for selecting some of the areas included also is not quite clear. For example, why should two chapters be devoted to Australia and none to Japan and Formosa? Furthermore, none of the islands off the western shores of South and Central America is represented.

A rather comprehensive bibliography is found at the end of each section. However, the almost complete absence of any documentation using these references is striking. A brief description in general terms of the geology of most of the areas discussed in this book is presented and should be of interest to geologists and geophysicists. The sections on meteorology, climatology, and topography for each area should also be useful to members of these professions when they have occasion either to visit or prepare exploration programs for any of the countries discussed in this book.

RICHARD A. GEYER

Einführung in die Physik der festen Erde (Introduction to the Physics of the Earth) by Dr. Hellmut Berg, published by S. Hirzel Verlag, Stuttgart, 1949, 295 pages.

This book represents another attempt to condense the information contained in some of the available compendia and periodical literature of geophysics. Admittedly this is one of the objectives as stated by the author in the preface but it is difficult to see why cognizance has not been taken of the progress made in both pure and applied geophysics as described in the literature of the past ten years or so. There is very little to be found in this volume which does not appear in books published previously of this type such as, for example, Tams "Grundzüge der physikalischen Verhaltnisse der festen Erde" ("Fundamentals of the Physical Conditions of the Earth") which appeared in two volumes, 1932 and 1937.

The section on instruments in the chapter on geomagnetics stops with the Schmidt vertical balance. No mention is made whatever of the airborne magnetometer which should prove to be a major factor in increasing our knowledge of the geomagnetic characteristics of the earth not only from the prospecting standpoint but from pure geomagnetism as well. In the section on the temperature of the earth the publications of Francis Birch and his contemporaries are conspicuous by their absence. In seismology the work of Ewing and his colleagues in the field of marine seismic studies is also ignored, as are the theoretical advances in wave propagation made by Pekeris.

One of the advantageous features of books of this type which have appeared in the past such as Tams; Meisser "Praktische Geophysik" ("Applied Geophysics") 1943; and Jung "Angewandt Geophysik" ("Applied Geophysics") 1948, has generally been the presence of extensive bibliographies which permit the reader to augment the information available in these digests. However, even this is missing and the bibliography; which includes "important geophysical periodicals," occupies less than a page. Upon examining the list of periodicals cited, a reason for some of the deficiencies mentioned above may be postulated. For example, such periodicals as *Transactions of the American Geophysical Union*, *Geophysics*, and the *Geophysical Supplement* of the *Monthly Notices of the Royal Astronomical Society* do not appear.

RICHARD A. GEYER

The Tectonics of Middle North America (east of the Cordilleran System), by Phillip B. King, Princeton University Press, Princeton, New Jersey, 1951, 203 pp., $3.75.

This latest publication of Phillip King arose from a "need for a modern description of the tectonic features of the United States for classroom use and as an explanation of the tectonic map of the United States" as stated in the author's foreword. The book is therefore essentially a textbook, at about senior collegiate level, and primarily useful in elucidating the features of the United States tectonic map. The reader should keep the author's purpose constantly in mind in order to evaluate the contents of the volume properly.

Mr. King is thoroughly qualified to write this book. He has been a geologist with the Geological Survey since 1930 and has made well-known contributions to geologic progress wherever he has concentrated his efforts. His work in West Texas is especially familiar to petroleum geologists. Moreover, he has already published "An outline of the structural geology of the United States" and he edited the "Tectonic Map of the United States."

The volume is divided into sections according to geologic provinces. The Central Stable Region, the Interior Lowlands, Paleozoic structures south and southeast of the Central Stable Region, and the Coastal Plains are discussed. In each stratigraphy and structure are considered. However, there is a distinct difference in approach to the writing of the section on Paleozoic structures as compared to the other sections. The Paleozoic structures are not only described but an attempt is made to arrange the geologic processes scientifically. That is, a sequence of events in time and space is developed so that prediction, part of the scientific method, can be made of structural and sedimentational conditions in unknown areas. This geologic philosophizing is essentially absent in the other three sections which are restricted to descriptions of tectonic features. As a consequence, approximately one hundred pages are devoted to Paleozoic structures and thirty to each of the three remaining sections.

The contributions of the three smaller sections on the Craton, Interior Lowlands, and Coastal Plains are therefore confined to the amplification of the tectonic map. These sections achieve that purpose. They may result in appearing fragmentary to a reader expecting a comprehensive discussion of the areas. In some instances, little geologic investigation has been carried out in the area, and the picture presented must rely on meager evidence. In other cases, a great amount of data is available but only the apparently significant results can be reported in a book of this type. Such spot sampling can lead to misconception. Furthermore, each bit of evidence must be thoroughly reviewed because so much importance is attached to it in a book of this type. For example, in the discussion of the Gulf Coastal Plain the statement is made that thinning gulfward of the Tertiary deposits is suggested by seismic and gravity observations. The late review of the geophysical evidence by the 1950 G.S.A. symposium on Gulf Coast sedimentation did not offer any such suggestions. The axis of the Gulf Coast geosyncline is still undefined.

The section on Paleozoic structures is the most interesting to read because it does go beyond the mere descriptive phase. In general, King tries to synthesize the sedimentation in a geosyncline, the structure in a tectogene, and the accompanying igneous activity into a unified geologic process. He attacks this problem by dividing the Paleozoic structures into four salients, Newfoundland, Northern Appalachians, Central and Southern Appalachians and the Wichita-Ouachita systems. He studies each one relatively closely and finds in each supporting evidence for the time and space relations necessitated by his thesis. Instead of attempting to present this complete thesis here, some incidental points of interest to the reviewer are noted below.

(1) Strong evidence is presented against the concept of simultaneous world orogenies, relatively sudden and of short duration. Instead, the case for more-or-less continuous deformation at different times and in different provinces is strongly defended.

(2) Apparently isolated basins, such as the Narragansett Basin, found within orogenic belts are developed as perhaps the latest phase of the orogeny.

(3) The role of the Gulf of St. Lawrence is very interesting especially to those connected with the petroleum industry. The counterparts of the structures on Newfoundland are found displaced much to the westward on the mainland so that the Gulf of St. Lawrence "must be underlain by major structural features of obscure character." Evidence for the displacement is also found in the submarine topography in the vicinity of the Grand Banks. King points out the striking similarity of this structural linkage with that between the Southern Appalachians and the Ouachita structures.

(4) The inclusion of the Ouachita as an Appalachian salient leads to the classification of the Ouachita sediments as eugeosynclinal and the Wichita sediments as miogeosynclinal. However, the Wichita structure system is at right angles to the Ouachita structural axis. This is explained, of course, by the thrusting of the Ouachita system over the Wichita system. But in every other case the eugeosynclinal and miogeosynclinal structures are parallel. All in all, the evidence for the thesis proposed by King is most abundant in Newfoundland and becomes less and less as one goes south. In the Ouachita area, the evidence is indeed so meager that the ideas proposed are controversial.

As stated in the beginning of this review, this book will undoubtedly become a standard textbook for senior collegiate geological courses. This reviewer sincerely welcomed the opportunity to take a refresher course in the geologic structural history of middle North America, and the refresher course was especially welcome because the material is presented very concisely and logically. A maximum amount of information is gained with minimum effort, and that alone is sufficient recommendation for reading this volume.

NELSON C. STEENLAND

"Radium and Deep-Sea Chronology," by Hans Pettersson, *Nature*, v. 167 June 9, 1951, p. 942.

This letter to *Nature*, coming from the Oceanografiska Institutet in Göteborg, Sweden, gives interesting new results on the sedimentation problem in the sea. The Swedish Deep-Sea Expedition has recently obtained new data on the concentration of uranium and radium in sea water. These

data confirm earlier results of a large deficiency of radium in equilibrium with uranium. The author had previously suggested this deficiency might be explained by the precipitation of ionium, the parent of radium. This precipitation would also account for the high concentrations of ionium and radium in red clay and some other surface deposits in the sea. By computing the amount of ionium precipitated and the concentration of ionium in the bottom sediment, the author has estimated the sedimentation rate to give the necessary dilution for this latter value. The sedimentation rate thus computed is 0.5 mm per thousand years for a core taken near Tahiti. It is suggested that this figure can be changed to 0.4 due to the diffuseness of the radium values from which the ionium concentration in the core was computed. The sedimentation rate is also computed by obtaining the decrease in ionium concentration with depth from the radium measurements. If this decrease is assumed to be due only to radioactive decay, the age versus depth curve is obtained for the sediments since the half life, or rate of disintegration, for ionium is known. The rate of sedimentation by this older method agrees with the above value of 0.4 mm per thousand years. Reports of the Swedish Deep-Sea Expedition will carry a more detailed account of this work.

LYNN G. HOWELL

"Measurements of Gravity in Ireland," by A. H. Cook, Department of Geodesy and Geophysics, Cambridge University, *Geophysical Memoirs* No. 2, Part 1, 1950.

Prior to the measurements described by the author, no observations of gravity had been made in Ireland. Measurements in Wales had shown that gravity increased toward the Irish Sea, whereas submarine observations in the Irish Sea gave somewhat lower values, and it was of interest to know how the gravity field of Ireland was related to that of Wales and the Irish Sea. In addition the values of gravity would be useful for geologic and geodetic purposes.

The apparatus used was the Cambridge pendulum apparatus designed by Sir Gerald Lenox-Conyngham which has been described in other publications (Lenox-Conyngham, 1928; Bullard, 1933; Bullard and Jolly, 1936; and Bullard, 1936). Two pendulums of period about 1.01 second swing together with equal amplitude and opposite phase so that sway disturbance is eliminated and ground movements do not perturb the mean of the two periods. To reduce damping and so enable small amplitudes to be used, the pendulums swing in an air pressure of about 30 mm Hg. The method of calculating the results is described in detail in this paper. In all, four stations were occupied by the pendulum apparatus.

While the pendulum observations were being made Mr. H. I. S. Thirlaway ran a gravimeter traverse around the four stations, a distance of approximately 400 miles. Difference in gravity between stations ranged from about 22 mgal to 143 mgal with the probable error being about ± 0.5 mgal. A report on the gravimeter survey is to be published as Part 2 of these memoirs. It is interesting to note that the standard deviation for both the pendulum and gravimeter is 0.5 mgal. It is regrettable that Mr. Thirlaway did not have a modern gravimeter for this survey. With such equipment this probable error would have been reduced by a factor of five or even ten.

The final results which are listed below are derived from data taken with the pendulum and the gravimeter. These results are expressed as differences of gravity from Cambridge, and using least squares they are:

Dublin, Dunsink Observatory	$+120.84 \pm 0.56$
Sligo, Courthouse	$+197.28 \pm 0.82$
Galway, University College	$+ 96.21 \pm 0.64$
Cork, University College	$- 22.51 \pm 0.87$

The value of gravity at Cambridge (Pendulum House) has been taken as 981.2650 cm/sec^2. No probable error for this value is given.

An excellent bibliography is included with this paper.

EUGENE FROWE

PUBLICATIONS RECEIVED

Listed below are all publications received at the business office of the society on subscription and through free exchange for *Geophysics* since publication of the last issue. Periodicals and separates indicated by the asterisk (*) have been forwarded to the Standing Committee on Reviews, and will be placed in the permanent depository of the society at the University of Tulsa Library. These publications are available for loan to members of the Society on application to the business manager. Other publications will be held for a short time at the business office. Disposition of books listed is by direction of the Standing Committee on Reviews.

Periodicals

**American Journal of Science*, Vol. 249, Nos. 4 through 8 (Apr.–Aug., 1951)
**Annales de Geophysique*, Vol. 7, No. 1 (June–Mar., 1951)
**Annali di Geofisica*, Vol. 4, Nos. 1 and 2 (Jan. and Apr., 1951)
**Boletin de la Asociacion Mexicana de Geologos Petroleros*, Vol. 2, Nos. 11 and 12 (Nov. and Dec., 1950)
Bulletin of the AAPG, Vol. 35, Nos. 5, 6, 7 & 8 (May–Aug., 1951)
**Bulletin of the Hungarian Geological Society*, Vol. 80, No. 10–12 (1950); Vol. 81, No. 1–3 (1951)
**Bulletin of the Seismological Society of America*, Vol. 41, No. 2 (April, 1951)
**Committee on Geophysics and Geography, RDB, Articles on Geophysics in Current Russian Periodicals*, List No. 31 (Apr. 18, 1951); List No. 32 (June 5, 1951)
**Deutsche Hydrographische Zeitschrift*, Vol. 4, No. 1/2 (1951); Jahresbericht No. 5 (1950)
Economic Geology, Vol. 46, Nos. 3, 4 & 5 (May–Aug., 1951)
**Erdöl und Kohle*, Vol. 4, Nos. 4, 5, 6 & 7 (Apr.–July, 1951)
**Geophysical Notes*, Tokyo University, Vol. 3, Nos. 16 & 19 (1950)
**Geofisica Pura e Applicata*, Vol. 19, Nos. 1–2 & 3–4 (Jan.–June, 1951)
**Geofysiske Publikasjoner*, Akademii Oslo, Vol. 17, No. 5–9
Institute of Petroleum Review, Vol. 5, Nos. 52, 53 & 54 (Apr.–June, 1951)
Journal of Applied Physics, Vol. 22, Nos. 5, 6, 7 & 8 (May–Aug., 1951)
**Journal of the Chinese Geophysical Society*, Vol. 2, No. 2 (Dec., 1950)
Journal of Geophysical Research, Vol. 56, Nos. 1 & 2 (Mar. & June, 1951)
Journal of the Institute of Petroleum, Vol. 37, Nos. 327, 328 & 329 (Mar.–May, 1951)
**Nafta*, Vol. 7, Nos. 2, 3, 4 & 5 (Feb.–May, 1951)
**Nuclear Science Abstracts*, Vol. 5, Nos. 8 through 16 (Apr. 30–Aug. 30, 1951)
**Proceedings of the Cambridge Philosophical Society*, Vol. 47, No. 3 (July, 1951)
**Quarterly Journal of the Geological Society of London*, Vol. 106, No. 2 (May 18, 1951)
**La Ricerca Scientifica*, Vol. 21, No. 3 (Mar., 1951)
Review of Scientific Instruments, Vol. 22, Nos. 4, 5, 6 & 7 (Apr.–July, 1951)
**Revue de l'Institut Français do Petrole et Annales des Combustibles Liquides*, Vol. 6, No. 5 (1951)
**Revista di Geofisica Applicata*, Vol. 12, No. 1 (1951)
**Science Reports of the Tohoku University*, Fifth Series, Vol. 2, No. 3 (Dec., 1950); Vol. 3, No. 1 (Apr., 1951)
**Rocznik Polskiego Towarazystwa Geologicznego*, Vol. 20, No. 1–2 (1950)
**Technical Data Digest*, Vol. 16, Nos. 6, 7, 8 & 9 (June–Sept., 1951)
**Tellus*, Vol. 3, Nos. 1 & 2 (Feb. & May, 1951)
**Transactions and Proceedings of the Geological Society of South Africa*, Vol. 53, (Jan.–Dec., 1950)

Books

Russell, *Principles of Petroleum Geology*, McGraw-Hill, New York, 1951
Proceedings of the Fourth Empire Mining and Metallurgical Congress, Part One and Part Two
Wells Shot for Velocity in West Texas, West Central Texas, Texas and Oklahoma Panhandles, San Juan Basin and Southeast New Mexico, Permian Basin Geophysical Society, Midland, Texas, 1951

DISCUSSIONS AND COMMUNICATIONS

HISTORICAL NOTE

Dr. Joseph A. Sharpe has called attention to a paper of considerable historical interest which appeared in Volume IV (1920) pp. 83–85 of the *Bulletin of the American Association of Petroleum Geologists*. Dr. Sharpe states, "This appears to be the first very clearly stated suggestion concerning the use of the seismic reflection method for the mapping of underground structure." The paper, entitled "Suggestions of a New Method of Making Underground Observations," is by Dr. J. A. Udden and is here reprinted in its entirety.

Bulletin Amer. Assoc. Pet. Geologists IV, pp. 83–85. 1920. Paper read at Dallas meeting March, 18–20, 1920.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

SUGGESTIONS OF A NEW METHOD OF MAKING UNDERGROUND OBSERVATIONS

J. A. UDDEN*

In the north-central part of the State of Texas, where wells are being drilled to the depth of 4,000 feet and more in order to penetrate the Bend formation (Pennsylvanian), which is the chief oil-bearing horizon in that part of the State, it has been found that the structure of the Bend and that of the underlying Ellenburger limestone (Ordovician) is quite generally the same. The plotting of under

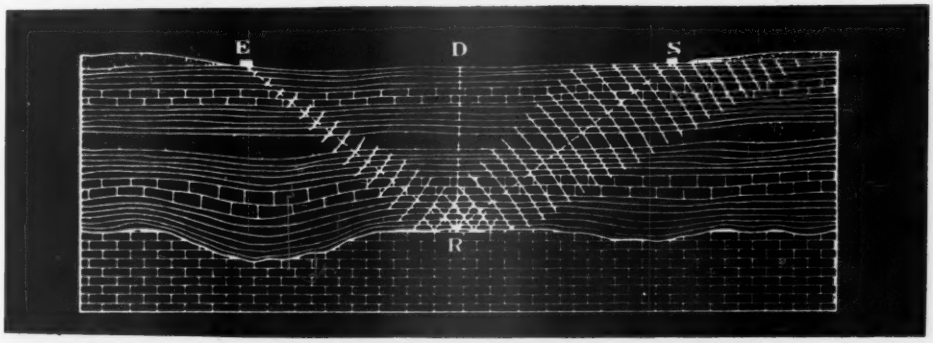


FIGURE 1. Reflection of earth waves, started at surface, from the contact between the Bend formation and the underlying Ellenburger limestone. E, point of explosion; S, position of seismograph; R, point of reflection of earth wave; RD, depth from surface to Ellenburger limestone.

ground structure by drillers' logs or by observations on cuttings from the Bend is very difficult, for the reason that there are small variations in the rocks of the Bend, not only vertically but also horizontally, and that these small variations lie near the limit between shale and limestone. Whether a certain part of the formation is reported as shale or as limestone will in large part depend upon the judgment and experience of the driller, or other observer. It has been exceedingly difficult to trace a definite horizon in the Bend with any considerable certainty. Exposures of the Bend indicate also that there are horizontal changes in this formation. For those who use drillers' logs in the making

* Dr. J. A. Udden, Director, Bureau of Economic Geology and Technology, Austin, Texas.

of structural maps, it has been found expedient to use the contact of the Bend and the underlying Ellenburger as the key horizon. Contours are drawn on the upper surface of the Ellenburger.

The top of the Ellenburger is a plane marking the greatest change of all the sediments in this part of the State. The Ellenburger itself is about 1,000 feet thick, where it is present in its full development, and almost all of this is one solid limestone. The Bend, which overlies it, is, as already stated, quite variable in its composition. In the San Saba country it has considerable limestone. West from here it becomes more and more shaly, and the same change is noticeable in a northerly direction, at least at some points. The Bend is overlain by the Strawn, Canyon and Cisco divisions of the Pennsylvanian. These consist largely of shale with some sandstones and limestones, and may collectively be characterized as much less uniform in composition than the Ellenburger. In the course of development in the Ranger-Desdemona field and other fields in this part of the State, it has become evident that the structure of the Bend does not always parallel the structures in the outcropping rocks and that therefore the prospecting of the Bend by the common geologic methods is not entirely satisfactory.

It has suggested itself to the writer that it ought to be possible, with present refinements in physical apparatus and their use, to construct an instrument that would record the reflections of earth waves started at the surface, as they encounter such a well-marked plane of difference in hardness and elasticity as that separating the Bend and the Ellenburger formations.

Some such instrument as a seismograph, especially constructed to be sensitive to vertical waves, possibly a slight adaptation of some of the present seismographs would be amply suitable for the purpose. A seismic wave might be started by an explosion at the surface of the earth, and a record of the emerged reflection of this wave from the upper surface of the Ellenburger limestone might be registered on an instrument placed at some distance from the point of explosion. The record would, of course, be a component of the direct and the reflected waves. It ought to be possible to notice the point at which the first reflection from the Ellenburger appears on a continuous record. The time of the record being known, it ought to be possible to figure the depth to the plane of reflection. It seems to me that by the making of a number of observations at points where the distance to the upper surface of the Ellenburger is known, it would be possible to learn to interpret the record correctly. It might be found necessary to make new adaptations on the working parts of the instrument. The difficulties ought not to be insurmountable. After these are once mastered, observations could be made anywhere, probably with quite rapid progress, and the entire upper surface of the Ellenburger might be mapped over wide areas with relatively small effort. The topography of the Ellenburger could, so to speak, be contoured directly by any number of observations desired. With such a topographic map of the surface of the Ellenburger, it seems to me that millions of dollars' worth of drilling could be eliminated, which will otherwise have to be done before all of the pools in the Bend shall have been located.

Why not pay twenty thousand dollars for "theoretical" experiments, if by so doing a million in expenses on "practical" work can be saved?

GEOPHYSICS IN HIGHWAY CONSTRUCTION

Dr. Sigmund Hammer has called attention to a very important paper relating to geophysics as used in highway construction. The paper is "Development of Geophysical Methods of Subsurface Exploration in the Field of Highway Construction" by R. Woodward Moore, Highway Engineer, Physical Research Branch, Bureau of Public Roads. It is published in *Soil Exploration and Mapping* issued as Bulletin No. 28 (1950) of the Highway Research Board, and it is obtainable through the Bureau of Public Roads, Department of Commerce, Washington 25, D. C.

PROFESSOR SYDNEY CHAPMAN'S LECTURE

The presence in the United States during the academic year 1950–51 of Professor Sydney Chapman of Oxford University permitted the Distinguished Lectures Committee of the Society to secure

the services of this outstanding authority on the magnetism of the earth as lecturer before most of the local sections of the Society.

During the eight day period, March 26 through April 2, Professor Chapman delivered his lecture, entitled "Survey of the Present Problems of the Magnetism of the Earth," to members of the geophysical societies and their guests at Denver, Tulsa, Houston, Dallas, Fort Worth, and Shreveport; conferred with individual geophysicists in these cities; and visited geophysical laboratories and manufacturing plants in Denver, Tulsa, Houston, and Dallas.

In the following condensation of the lecture, prepared from a written text provided by Professor Chapman, particular emphasis has been given to Professor Chapman's views concerning the present theories of the earth's magnetism.

SURVEY OF THE PRESENT PROBLEMS OF THE MAGNETISM OF THE EARTH

Historical

The Greeks first observed magnetic and electric attractions, but it was not until the twelfth century that manuscripts noted the *directive* property of the magnet. The French soldier-scientist, Petrus Peregrinus, first described the dipolarity of the magnet in a famous letter. Petrus believed, however, that the compass pointed towards the true pole of the heavens. A Portuguese, Juan de Castro, made detailed observations of the earth's magnetic declination in 1543–45. The magnetic dip was discovered by Robert Norman in 1576, and he concluded that the controlling influence was within the earth.

The Earth a Magnet

In 1600 William Gilbert published his treatise *de Magnete* in which he expressed his discovery that the terrestrial globe is itself a great magnet. Gilbert thus fathered the science of terrestrial magnetism. He clearly recognized the big problem: *why is the earth a great magnet,* and the secondary problem *why is its magnetism not quite regular.*

The Secular Variation

Within thirty years, Gellibrand had discovered the secular magnetic variation, and a few decades later Edmond Halley, the astronomer, proposed a theory for secular variation. He pictured a fantastic earth formed of an inner core surrounded by one or more shells, each magnetized differently, rotating at different rates about different axes.

Magnetic Maps

To check his theory, Halley made the first scientific voyage—a magnetic survey of the North and South Atlantic Oceans. On his return he published the first isogonic chart, and a few years later Halley produced a world magnetic chart. About 1890 van Bemmelen, using early naval records, constructed declination charts for epochs from 1500 A.D. onwards at 50 year intervals.

The Dipole Field

By 1836 the French Admiral Duperrey had drawn maps showing the lines of horizontal magnetic force on the earth's surface, and by that time Poisson had developed the theory of magnetic potential. The great German mathematician Gauss confirmed mathematically that the earth's magnetic field proceeds from within, and that, to a first approximation, the field is that of a uniformly magnetized sphere, or a magnetic dipole, at outside points. Gauss showed for the first time how to measure the magnetic intensity in terms of units of length, mass, and time, and he set up the first magnetic observatory.

The Non-Dipole Field

Although the earth's field is approximately a simple dipole field, divergences from this are important enough to form, together with the main field and the secular variation, the third main problem

of the subject. The non-dipole field, namely the vector difference between the earth's field and the best fitting dipole field, can be represented by maps which show its regional character and complexity.

Isoporic Maps

The secular change of the earth's field can likewise be represented on maps by lines of equal rate of change, or isopors. At present, the regions of decreasing intensity exceed those of increasing intensity, and in the last century the dipole field has decreased by about five percent.

Local Anomalies

Some of the anomalies of the earth's field are certainly due to magnetic deposits not far from the surface of the crust. But other major regional anomalies are present which gradually change their force and location, and it is difficult to believe these can be explained by crustal magnetism.

Paleomagnetism

The researches of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington have extended the time-span of our knowledge of the earth's magnetism. The results obtained are consistent with the idea that for 50 million years or more the earth's magnetic polarity has had an average direction nearly coinciding with that of its axis of rotation. These conclusions as to the stability of the general direction of the earth's magnetization are supported also by similar researches on sediments taken in cores from the bed of the ocean. A contrary indication is given by some volcanic dikes in South Africa, Northern England, and elsewhere. These dikes show strong magnetization of a sign opposite to that of the present day field, and the apparent contradiction is as yet quite unexplained and mysterious.

Rotational Theories

Kelvin in 1883 speculated on the cause of the earth's magnetism, and concluded that it must be connected with its *rotation* and its *bigness*. But even rapidly rotating bodies, in the laboratory, show a degree of magnetization so small that the effect defied detection until discovered by the delicate experiments of S. J. Barnett some twenty-five years ago. This "Barnett effect" is too small to explain the earth's field.

Other rotational hypotheses of a fundamental character have been proposed to explain the earth's dipole component along the geographic axis. For example, the centrifugal force caused by the earth's rotation will cause the planetary electrons in the atoms of the earth to lie farther from its center, on the average, than the positively charged nuclei, thus producing a net electric field. But this effect fails to account for the earth's field by more powers of ten than the Barnett effect.

Solar and Stellar Magnetism

The discovery of magnetism in the sun by Hale at Mt. Wilson, first in sunspots, and then the general magnetic field, gave added stimulus to attempts at explanation of cosmic magnetism, particularly as the sun's field was related to its rotation in the same way as for the earth. For example, Blackett's hypothesis implied that the rotation of electrically neutral matter would produce a magnetic field *as if* the matter were negatively electrically charged and by its rotation would constitute an electrical current system. Bullard pointed out that if this were so, the outer layers of the earth would contribute their share to the field of these non-existent but magnetically effective quasi-electric currents. Therefore, downward through these layers the earth's field would, on this hypothesis, change in a manner different from that usually supposed (the inverse cube law). Specifically, calculation showed that the vertical force, not far below the surface, should still increase in the same way on the new hypothesis as on the old, but that the horizontal force should at first *decrease* downwards, instead of increasing. Blackett actively promoted measurement of the earth's field in mines, and it gradually appeared that the hypothesis would not work. The experiments led to the definite proof that the outer non-magnetic layers of the earth do *not* contribute to the field. Meanwhile the fundamental type of theory of magnetization by rotation received a hard blow from Babcock's discovery

of a star with a polar field of several thousand gauss which reverses its magnetization almost symmetrically every nine days.

Electric Currents as the Cause of the Earth's Field

Another possible explanation of the earth's magnetism ascribes it to electric currents. Currents in bodies of large size decay slowly, but even so the half life of a current system such as could produce the earth's field is short compared with the age of the earth. Hence, if electric currents produce the earth's field, they must be continuously maintained. Larmor in 1919 suggested that electric currents such as seem likely to be the cause of the earth's and the sun's magnetic fields may be due to *dynamo action* by convective motion in their fluid interiors in the known presence of their magnetic fields. In the earth's liquid core (the diameter of which is 0.55 times that of the earth), convection is likely to be produced by radioactive transformations even if the concentration of radioactive matter there is much less than the observed amount in the crust of the earth. Motion of matter in a magnetic field necessarily sets up electromotive forces which impel electric currents if the matter is conducting. Larmor suggested that convection in meridian planes might thus set up electric currents around the earth's axis which would *maintain* the component of the dipole field along the axis of rotation, or even cause it to *grow* from small beginnings such as the Barnett effect would produce, precisely as in a self-exciting dynamo. Cowling, however, has shown that convective motion in meridian planes, symmetrical about the magnetic axis, cannot maintain the axial dipole field.

During the last decade, Elsasser has devoted much effective effort to the theoretical study of the earth's magnetic field, and more recently Bullard has made further advances, partly along lines considered by Elsasser. The present position seems to be that the component of the main dipole field which lies along the earth's geographical axis is still not definitely explained, but that there is hope of explanation in a dynamo theory on the basis of an unsymmetrical convective motion.

The Non-Dipole Field and Secular Variation

The secular variation, though slow by human reckoning, is extremely rapid compared with the geological changes in the earth's crust. It points to changes in the earth's interior which are so rapid as to be most naturally ascribed to the liquid core, where there is sufficient fluidity to permit relatively rapid change. In nature most motions are to some extent turbulent, and it may be supposed that any large scale convection in the core is accompanied by smaller scale eddies superposed thereon. These will have their own additional dynamo effect, superposing smaller scale systems of electric current on the main system. The non-dipole field may be taken as indicating the presence of such subsidiary electric current systems in the core; and as the eddy motion and the resulting electric currents will change, this will produce the secular variation. It seems likely that the effective eddies and their electric current systems are those that lie near the outer surface of the core, because changing magnetic fields produced deep in the core would induce secondary electric currents in the outer layers, preventing these fields from extending outside to any appreciable degree.

By spherical harmonic analysis Vestine has approximately indicated the distribution of electric currents near the surface of the core that could be responsible for the earth's surface field. McNish has shown that the non-dipole field could be produced by about 14 dipoles, the moment of each being approximately one-hundredth that of the main field, situated near the surface of the core. Their dipole moments indicate something as to the intensity of the equivalent electric current systems, each extending over about one-fourteenth of the surface of the core. Bullard has estimated the dipole moment and electric current eddy that could produce the rapid secular magnetic variation over and near the southernmost part of Africa.

The electric current eddies and conductivity of the core being thus estimated, the electromotive forces may be inferred. According to the dynamo theory, these depend on the product of the speed of motion in the convective eddies and of the magnetic intensity in the core. According to the inverse cube law, the magnetic intensity at the surface of the core should be about 4 gauss. If this is also valid inside the core, the eddy speeds required are of the order of a meter an hour. This, however, is

only the component speed perpendicular to the magnetic field, and there may be a considerably greater component along the field.

The Toroidal Field Inside the Core

There is some reason to suppose that the magnetic field inside the core is perhaps ten times as intense as that just outside, and that its character also is different from that inside a uniformly magnetized sphere, for which the lines of force (inside and outside) lie in meridian planes. It is thought that inside the core the lines of force are much twisted around the axis, so that the field has a considerable "toroidal" component around the axis, which does not extend at all outside the core. This twisting of the lines of force is attributed to a slight differential rotation of the core relative to the solid outer mantle of the earth, whose rotation is being very gradually slowed down by tidal friction. In a medium as electrically conducting as the core is supposed to be, the lines of magnetic force remain always attached to the same elements of the fluid, and therefore share in the distortion that a differential rotation would produce. A convective eddy motion would also twist the lines of force, increasing the intensity of the magnetic field at the expense of the kinetic energy.

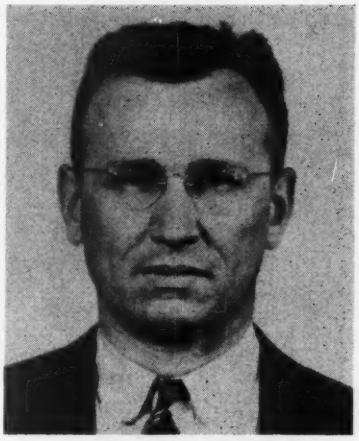
Conclusion

At the present time the theories of the earth's main magnetic field, its major anomalies, and secular variation are in a decidedly tentative state. The two latter are attributed to changing electric current systems maintained by the dynamo action of changing hydrodynamic eddies near the surface of the earth's core. The main field is thought, but not yet proved, to be produced by a main system of convective motion, not confined to meridian planes, in the earth's core. The westward movement of the secular variation and the decrease of the earth's dipole moment during the past century are thought to be transient features.

Plea to Exploration Geophysicists

Exploration geophysicists can assist the progress of the "pure" science of geomagnetism in a number of ways. For instance, they can deposit magnetic data with geomagnetic institutions or libraries, or they can publish such data in summary or outline. In addition, they can use their technical experience in the design of instruments to aid, by advice and discussion, in the much needed modernization and re-equipment of magnetic observatories.

CONTRIBUTORS



W. B. Agocs

W. B. Agocs received the B.S. in E.M. majoring in Mining Geology in 1934, the M.S. and Ph.D. in Physics in 1944 and 1946, respectively, all from Lehigh University. During 1943 and 1944, he was Instructor in Physics and Geophysics at Lehigh University. From 1934 to 1940, he was a geophysicist for the Gulf Research and Development Company. The major part of this period with G.R.&D.C. was spent in Venezuela as Party Chief—Geophysicist on research refraction and reflection seismograph parties.

In 1945, 1946 and 1948, 1949, Dr. Agocs was Chief Geophysicist for the Venezuelan Atlantic Refining Company. During 1947 and 1948, while at Lehigh University, and during 1950 he was a geophysical consultant. Since September 1950, Dr. Agocs has been Associate Professor of Physics and Geophysics at the University of Tulsa, and a Geophysical-Geological Consultant.

Dr. Agocs is a member of the Institute of Radio Engineers, American Institute of Physics, Sigma Xi, and Society of Exploration Geophysicists.

Kenneth E. Burg

Kenneth E. Burg received his B.S. degree in Electrical Engineering from the University of Texas in 1926. Upon graduation he was employed by The Geophysical Research Corporation to do experimental geophysical work. Mr. Burg was computer and observer on one of the original experimental reflection crews and was in charge of several electrical prospecting crews prior to the time he was made Party Chief on a large refraction crew in 1928.

In 1930 he resigned to join the newly-formed Geophysical Service Inc. As Party Chief with that organization, he worked in the Gulf Coast, Mid-Continent, and Pacific Coast areas, and in Canada. He was placed in charge of the Southern Louisiana and Mississippi areas as District Supervisor in 1936, where he was instrumental in developing the techniques and equipment used in that area. In 1941 he was placed in charge of the Research Department in the Dallas Laboratories of Geophysical Service Inc.

Mr. Burg resigned in 1942 to join the Stanolind Oil and Gas Company as Seismograph Technician. In 1943 he was made head of the Seismograph Department, and in 1944 promoted to Geophysical Supervisor in charge of all the geophysical operations of the Stanolind Oil and Gas Company. He rejoined Geophysical Service Inc. in January 1947, as consulting Geophysicist. In 1950 he was promoted to Vice President, Technical, and in charge of equipment, field and office techniques and research.

Mr. Burg is a member of the Society of Exploration Geophysicists, American Association of Petroleum Geologists, American Geophysical Union, Seismological Society of America, The Dallas Geophysical Society, Institute of Radio Engineers, and Tau Beta Pi Honorary fraternity. He has served on the Research Committee of the American Association of Petroleum Geologists, and has served the S.E.G. as a member of the regional program committee, as chairman of the Standing

Commitee on Membership, in the preparation of the Cumulative Index and as Secretary-Treasurer of the Society. He has also served as Vice-President of the Dallas Section and Chairman of the Program Committee for the first Dallas Regional Meeting.

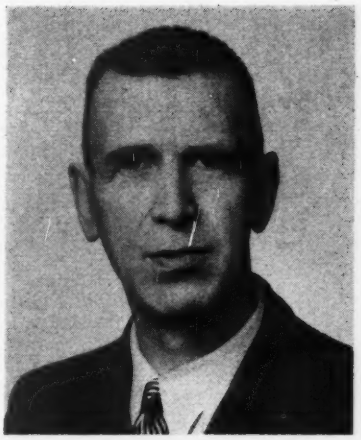
SYDNEY CHAPMAN

SYDNEY CHAPMAN studied engineering at Manchester University, mathematics at Cambridge, was chief assistant at the Royal Observatory at Greenwich, Fellow and Lecturer at Trinity College, Cambridge, and professor of mathematics and natural philosophy at the Universities of Manchester, London and, at present, Oxford. Professor Chapman is a Fellow of the Royal Society of London, Foreign Member of the National Academy of Sciences, Washington, President of the International Association of Terrestrial Magnetism and Electricity, and in previous years served the Royal Meteorological Society, the London Mathematical Society, the Royal Astronomical Society, and the Physical Society of London as President. After a year as Research Associate at California Institute of Technology, he appeared before the Denver, Tulsa, Dallas, Fort Worth, Shreveport, and Houston Local Sections in a distinguished lecture tour sponsored early this year by the Society of Exploration Geophysicists.

J. HARVEY CROSS

J. HARVEY CROSS was born May 7, 1924, in Chicago, Illinois. In September, 1940, he entered Oberlin College, Ohio and attended school until he was drafted into the Armed Forces in March, 1943. He served approximately three years as a rifleman with the 11th Air Borne Infantry Division, 511th Regiment, including 18½ months in the Southwest Pacific Area. After an honorable discharge in November, 1945, he entered the University of Texas where he held a teaching fellowship. After he received a B.S. degree in physics in June, 1948, he accepted the position of a Junior Physical Engineer with the Magnolia Petroleum Company. In April, 1949, he resigned this position to reenter Texas University for graduate work in geophysics. During the past year he has been working on his thesis as a Research Scientist Class I under a Navy research contract (N6onr-266, T. O. VIII). This project is also being supported by yearly research grants from the Humble Oil and Refining Company and the Shell Oil Company. He accepted a position with the Humble Oil and Refining Company as a Junior Exploration Geophysicist after having graduated with a M.A. degree in June, 1951.

Mr. Cross is a member of the Society of Exploration Geophysics, American Geophysical Union, and Sigma Pi Sigma.



FRITZ GASSMANN

FRITZ GASSMANN received his diploma in Mathematics and Physics in 1923, and his Ph.D. in Mathematics in 1925, both from the Swiss Federal Institute of Technology, Zurich (Switzerland). In the period 1925–42, he was at first assistant at the Swiss Federal Earthquake Service, then teacher and rector of the Kantonsschule Aarau and instructor for Geophysics at the Swiss Federal Institute of Technology. Further training in Geophysics led him to Jena, Naples, and Freiburg. Since 1942 he has been professor of Geophysics and director of the Institute of Geophysics at the Swiss Federal Institute of Technology, Zurich.

CLARK GOODMAN

CLARK GOODMAN was born September 9, 1909, in Memphis, Tennessee. He received the B.S. in Chemical Engineering at California Institute of Technology in 1932, and the Ph.D. in Physics at Massachusetts Institute of Technology in 1940. From 1932 to 1933 he served as research chemist for Union Oil Company; from 1933 to 1936 in the same capacity for the Kelco Company; from 1940 to 1942 as research associate, 1942 to 1947 as assistant professor, and from 1947 to the present time as associate professor at Massachusetts Institute of Technology. He was consultant for the Manhattan District from 1943 to 1946; Technical Aide, Division 17, NDRC in 1945 and 1946; and Senior Physicist, Clinton Laboratories, Oak Ridge, Tennessee, in 1946.

Dr. Goodman is a Fellow of the American Physical Society and the Geological Society of America.

W. HEISKANEN

W. HEISKANEN was born in Kangaslampi, Finland in 1895. He received the degree of Ph.D. from the University of Helsinki in 1924. From 1921 to 1928 he served as geodesist with the Finnish Geodetic Institute. He has been Assistant Professor of Geodesy at the University of Helsinki since 1926, and was Professor of Geodesy at Finland's Institute of Technology from 1928 to 1949. He has served as Director of the Isostatic Institute of the International Association of Geodesy since 1949, and as Reporter on Isostasy of the Association since 1930.

Dr. Heiskanen was a Member of the Finnish Parliament from 1933 to 1936. He has been a member of the Finnish Academy of Sciences since 1928; member of the Board of the Finnish Cultural Foundation since 1937; honorary member of the Dutch Geographical Society since 1938; member of the American Geophysical Union and American Geographical Society since 1946; member of the Norwegian Academy of Sciences of Bologna since July 1950; and member of the Academia Nazionale dei Lincei in 1951. He has served as President of the Finnish Geographical Society, Finnish Astronomical Society, and Finnish Society of Christian Culture. He was Research Associate with the California Institute of Technology in 1948. Among the honors he has received are: Commandeur, Finnish White Rose, Estonian White Star, and Hungarian St. Stephan.

Dr. Heiskanen has published five textbooks and about seventy-five scientific investigations on geodesy, gravimetry, and astronomy.

DARRELL S. HUGHES received his A.B. and M.S. degrees from the University of Kentucky in 1926 and 1928 and his Ph.D. degree from the University of Chicago in 1931. During the years 1931–1933 he held a National Research Fellowship at the California Institute of Technology. After one year of teaching and one year on production research with the Kettleman North Dome association, he joined the Shell Oil Company as chief of a gravity party. During the next ten years he worked on the interpretation of gravity, seismic, and electric data, and the design and development of instruments. In September 1945, he joined the staff of the Physics Department of the University of Texas as Professor of Physics. Since that time he has been engaged principally in research on physical properties of rocks and minerals at high pressure and temperature.

DARRELL S. HUGHES

HAROLD R. PRESCOTT

HAROLD R. PRESCOTT received his B.S. degree in Electrical Engineering from the University of Kansas in 1927.

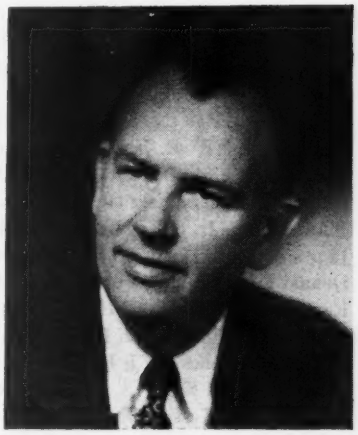
He has been engaged in geophysical work since 1927, when he was employed by the Marland Oil Company in connection with gravity pendulum development. Employment continued with Continental Oil Company, following its merger with the Marland Oil Company, in the capacity of Development Geophysicist. In 1949 he became Assistant Manager of the Geophysical Department of Continental Oil Company and in June 1951 was promoted to Manager of the Geophysical Section.

He is a member of the Society of Exploration Geophysicists, the S.E.G. Houston Section, the American Association of Petroleum Geologists, and the Houston Geological Society.

D. J. SALT

D. J. SALT was graduated from the University of Toronto in 1948 in Engineering Physics. The summer of 1948 he spent on the Seward Glacier in Alaska and the Yukon, conducting seismic operations. In November 1948 he joined Mining Geophysics Corporation interpreting aeromagnetic surveys and conducting field work. In March 1951, he organized Geo-Explorers Ltd., of which he is now managing director.

Mr. Salt is a member of the Association of Professional Engineers of Ontario, the Arctic Institute of North America, and the Society of Exploration Geophysicists.



E. J. STULKEN

E. J. STULKEN was born and reared in Texas. He studied mathematics and physics at The University of Texas, receiving there his B.A. degree in 1934 and his M.A. degree in 1935. From 1935 to 1940 he was employed by Geophysical Service, Inc. in the capacity of computer. During the following two years he served at Allen Military Academy, Bryan, Texas, as Instructor of Mathematics and Physics. Since 1942 he has again been associated with Geophysical Service Inc. serving successively as Chief Computer, Seismologist, and Chief Seismologist. Here he has worked chiefly on seismic computing methods and on special problems of interpretation.

Mr. Stulken is a member of the Society of Exploration Geophysics, The Mathematical Association of America, The Dallas Geological Society, and the Dallas Geophysical Society.

SOCIETY ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the society. This publication does not constitute an election but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the president within thirty days. Names of the references appear in parentheses after the name of each nominee.

ACTIVE

Charles Harry Carlisle (D. H. Gardner, H. G. Patrick, M. M. Slotnick)
Charles Burton Cox (Vincent Miller, R. M. Bradley, C. L. Brownlow)
Tobias Flatow (D. H. Gardner, H. G. Patrick, M. M. Slotnick)
Theodore Burroughs Fryer, Jr. (H. C. Bemis, R. C. Dunlap, G. J. Hulsewe)
Robert Alvey Hall (J. C. Waterman, H. R. Thornburgh, Robert Dyk)
Robert Linders Heineck (R. W. Mossman, H. M. Thralls, H. H. Andrews)
Weikko Aleksanteri Heiskanen (Sigmund Hammer)
Ralph C. Howard (John E. McGee, J. T. Murrell, W. B. Lee, Jr.)
Fred Thomas Kafka (Leo J. Peters, L. W. Gardner, C. H. Dresbach)
John Frederick McFarlane (Earle W. Johnson, T. O. Hall, Jack Martin)
Frederick Allan McKinnon (A. D. Dunlap, H. W. Stoneman, Tom D. Mayes)
Melvin John Rieger (Roy L. Lay, Vernon E. Briard, R. N. Buryere)
Benjamin Boags Robinson, Jr. (C. R. Lowe, David Bell Campbell, Ralph S. Jackson)
Ralph Thomas Smith (J. E. Lee, Jr., V. G. Feather, J. C. Palmer)
Paul Harris Steed (E. V. McCollum, T. J. Thomas, Craig Ferris)
Donald Desmond Utterback (Paul S. Lewis, John D. Marr, Karl W. Abel)
Cornelis Jan Velzeboer (Ch. Dresbach, A. van Weelden, P. Mrosovsky)

ASSOCIATE

Robert Berry Arnold (R. G. DeGood, E. J. Handley, L. D. Ervin)
Adrian Anthony Becker (John M. Crawford, Roland F. Hughes, Bird G. Swan)
Owen Burtis Bennett (A. I. Innes, Andrew Gilmour, Albert Taylor)
Henry Stinson Birdseye (Leland C. Adams, Joseph Fishback, K. C. Thompson)
Louis David Blom (A. Klaveness, C. C. Zimmerman, H. W. McDonnold)
Leonard Keith Buller (Sidon Harris, R. H. Dana, Elmer F. Blake)
Julian Martin Busby (Erdelyi Fazekas, David Reed, William B. Pine)
Troy Norman Crook (W. B. Duty, R. A. Lowery, Robert S. Duty, Jr.)
Julius Perry Edge (N. K. Moody, R. G. Harbach, R. F. Aldridge)
Betty Gaines (W. E. Jasper, O. B. Jackson, L. F. Fischer)
Marvin Grace (A. B. Hamil, Gordon Mace, Sam Pena)
Robert James Graebner (R. C. Dunlap, Jr., Paul E. Swenson, T. P. Ellsworth)
John E. Hall, Jr. (R. F. Bennett, R. D. Roberts, C. B. Smith)
James Kenneth Harrison (A. Klaveness, C. C. Zimmerman, H. W. McDonnold)
Donald Edwin Heilner (Kenneth E. Burg, Robert C. Dunlap, Jr., Homer L. Heggy)
Ray Joseph Hope (T. O. Hall, Chester Sappington, Ronald Wright)
James Richard Hunt (H. E. Itten, C. J. Long, P. H. Garrison)
George Roy Jones (E. J. Handley, R. G. DeGood, Orville Strozier)
Patrick Francis Kelly (S. E. Giulio, R. F. Weichert, R. J. Watson)
Eugene Louis Kessler (Karl Dyk, M. B. Widess, H. E. Itten)

Thomas Carroll King (R. M. Dreyer, T. G. Arnold, Craig Ferris)
Joseph Cowden Knight (Thomas O. Hall, John P. Paschall, M. R. Henderson)
Morris Andrews Long (R. T. Gallagher, S. A. Spencer, W. B. Agocs)
Vincent D. Mackle (L. F. Athy, H. R. Prescott, W. C. Kimball)
Richard George Martin (Carl W. Blakey, Thomas A. Manhart, B. W. Beebe)
Robert Barnard O'Connor, Jr. (F. Goldstone, C. H. Gregory, W. Hafner)
Budd Orlich (Thomas A. Manhart, B. Warren Beebe, Carl W. Blakey)
Everett Horace Parker, Jr. (J. G. Harrell, A. E. McKay, Sidon Harris)
Sam Walker Patterson (R. G. Reiser, C. M. Wert, G. R. Belt)
Thomas Bruce Portwood, Jr. (R. F. Weichert, C. N. Hurry, W. W. Clark)
Louis Victor Provensal (Roy L. Lay, A. A. Hunzicker, B. H. Treybig, Jr.)
Aubrey Henry Rabensburg (L. L. Nettleton, C. B. Claypool, J. A. Culbertson)
Robert William Riedel (W. A. Longacre, L. O. Bacon, B. H. Boyum)
Harold Herbert Sawyer (Judson Mead, Andrew H. McNair, Charles Deiss)
Eugene Theodore Schnieder (R. W. Mossman, H. M. Thralls, H. H. Andrews)
John David Sistrunk, Jr. (U. A. Rowe, Chester Sappington, E. W. Johnson)
Melvin Mathein Smith (Harold K. Herr, Deane J. Wolff, H. L. Mendenhall)
Mohammed Wafick (J. R. Cornett, Sam D. Rogers)
Warren Alton Wilson (J. G. Harrell, A. E. McKay, Sidon Harris)

TRANSFERS TO ACTIVE

Jacobus Willem De Bruyn (A. van Weelden, B. Baars, V. P. Ulrich)
Richard Longley Fentem (A. I. Innes, Andrew Gilmour, Albert Taylor)
Kasmier Dominic Kubik (A. B. Hamil, G. M. Mace, Jr., B. K. Johnson)
Wallace Edward Pennington (A. I. Innes, Andrew Gilmour, A. W. Taylor)
Robert Frank Pomeroy (Leo J. Peters, Sigmund Hammer, Thomas A. Elkins)
John Joseph Schneider, Jr. (Chester P. Sappington, Thomas O. Hall, Roy F. Bennett)
Merrill Smith (Roy L. Lay, C. R. Wallace, A. A. Hunzicker)

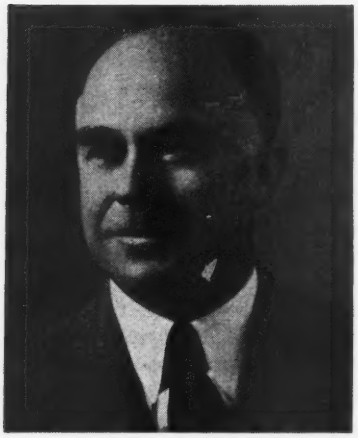
TRANSFERS TO ASSOCIATE

John Mike Donna (James B. Macelwane, Kenneth E. Burg, Fred J. Agnich)
Harold Lloyd Krivoy (H. V. W. Donohoo, Henry R. Joesting, Philip Donnerstag)

NOMINEES FOR 1952–53 EXECUTIVE COMMITTEE

The following brief biographical sketches are presented to acquaint members of the society with nominees appearing on the official ballot which will be mailed to all voting members at a later date.

FOR PRESIDENT



CURTIS H. JOHNSON

GERALD H. WESTBY

CURTIS H. JOHNSON was graduated from the University of California at Los Angeles in 1932 with an A.B. and Honors in Physics, and took postgraduate work in acoustics also at U.C.L.A. From 1933 to 1938 he was geophysicist and later chief geophysicist with Rieber Laboratory. From 1939 to the present date he has been employed by General Petroleum Corporation where he currently holds the position of assistant chief geophysicist.

Mr. Johnson is a member of the Society of Exploration Geophysicists, The American Association of Petroleum Geologists, and the American Geophysical Union. He has served the S.E.G. as vice chairman of the arrangements committee for the national convention in Los Angeles in 1947, chairman of the program and arrangements committee for the 1947 Pacific Coast Regional Meeting and chairman of the Pacific Coast program committee for the 1948 annual meeting. In 1948 he participated in the organization of the Pacific Coast Section of the Society of Exploration Geophysicists and was elected its first president. He is at present Vice President of the Society of Exploration Geophysicists, and is General Chairman of the program and arrangements committee for the Twenty-Second Annual Meeting which will be held March 23–26, 1952, in Los Angeles.

His other recent activities on behalf of the society include membership on the Standing Committee on Honors and Awards, 1949–50 and 1950–51, and as member-at-large on the Standing Committee on Program and Arrangements for the 1951 annual meeting.

GERALD H. WESTBY was born in Stoughton, Wisconsin, of Norwegian-English parents, on August 4, 1898. He received his elementary education in the LaCrosse, Wisconsin, public schools and was graduated from high school there in 1916. He attended the University of Chicago and, because of the influence of Professor R. D. Salisbury, majored in geology. He was graduated from the University of Chicago with his class in 1920, since credit was given for army service in the Coast Artillery Officers Training School, Fort Monroe, Virginia, where he received a commission as Second Lieutenant.

In the summer of 1920, Mr. Westby taught physiography and geography at the University of Montana, and early in the fall left to accept a position with S. Pearson & Son, London, England, to

do geological work on various assignments throughout the world. From late 1920 to early 1924, he was resident geologist for S. Pearson & Son in Algeria. After completing three months of research work at Stanford University, Mr. Westby accepted a position as field geologist with the Empire Oil and Refining Company, with field headquarters at Denver, Colorado. In the fall of 1926 and in early 1927, while still employed by Empire, he attended the first class in geophysics to be offered at the Colorado School of Mines. In late 1927 he was made chief geophysicist of the Empire Oil and Refining Company and maintained that position until September 1933.

Since 1933 Mr. Westby has been associated with Seismograph Service Corporation, Tulsa, Oklahoma, and has been president of the company since 1935. He is also president of Seismograph Service Corporation of Canada, operating in that country, Seismograph Service Corporation of Delaware, operating in Mexico and Venezuela, and chairman of the board of directors of Seismograph Service Limited, an English subsidiary operating in the Sterling Bloc areas.

Numerous articles by Mr. Westby have been published in the trade magazines and several in the early issues of the Society publications.

Mr. Westby is a member of the Society of Exploration Geophysicists, the Geophysical Society of Tulsa, The American Association of Petroleum Geologists, the American Geophysical Union, the American Association for the Advancement of Science, and the American Institute of Mining and Metallurgical Engineers. He was mid-continent representative on the Founding Committee of the Society of Exploration Geophysicists and is, therefore, a charter member. He served the Society as secretary-treasurer in 1935–1936 and as vice president three times (1931–1932, 1932–1933, and 1936–1937).

FOR VICE-PRESIDENT

O. C. CLIFFORD, JR.

ROY L. LAY

ROY L. LAY received his B.S. degree in Electrical Engineering from Rice Institute in 1928. Upon graduation from Rice he was employed by the Geophysical Research Corporation as an observer and was later promoted to computer and party chief.

Mr. Lay was employed by The Texas Company as party chief in April, 1932 and during the next several years initiated this company's reflection work in Texas, Louisiana, California, and the Rocky Mountain area. He was promoted to field supervisor in 1937, and during the next year made a supervisory trip to Colombia and Venezuela, and was in charge of the seismic, gravity and magnetometer work in Egypt. In July, 1943 he was promoted to assistant chief of the geophysical division and in September, 1945 was advanced to the position of assistant manager. On April 1, 1950 he became

manager of the geophysical division, the position which he now holds, having jurisdiction over The Texas Company's geophysical operations in the United States and Canada.

He is a member of the American Association of Petroleum Geologists, Houston Geological Society, and has been a member of the Society of Exploration Geophysicists since 1935. He was Second Vice-President of the S. E. G., Houston Section, in 1947–1948, President for the 1948–1949 term, and served on the executive committee of that section from 1949 to 1951.

O. C. CLIFFORD, JR., received his first two years collegiate work at the University of Wyoming. He was graduated from the University of Chicago in 1924 with a B.S. in Geology, remaining at that institution the following year engaged in graduate study. He was employed in 1925 by Humphreys Corporation on one of the earliest torsion balance parties. Between 1926 and 1933, he held positions in gravity, magnetics, seismics, and subsurface geology for a variety of companies with experience in all of the oil producing states of the Mid-Continent. In 1934 he was employed by Continental Oil Company as control geophysicist with headquarters in Ponca City, Oklahoma. In 1936, he joined The Atlantic Refining Company as district geophysicist for the Gulf Coast area of Texas. In 1943, he was transferred to the main office in Dallas as chief geophysicist, the position he currently holds.

Mr. Clifford is a member of the Society of Exploration Geophysicists, The American Association of Petroleum Geologists, and the American Geophysical Union. He has served the S. E. G. as a District Representative, and as a member of the editorial board of the Case Histories volume. He is a past president of the Dallas Geophysical Society. He has written for the A.A.P.G. bulletin and is represented as a co-author in *Geophysical Case Histories, Volume One.*

FOR SECRETARY-TREASURER

CARL L. BRYAN

JAMES L. MORRIS

CARL L. BRYAN was born in Guadalupe County, Territory of New Mexico, on August 10, 1908. Three years of undergraduate work in electrical engineering at the University of Texas were followed by employment in June 1928 in the geophysical department of Gulf Production Company at Houston. He was transferred to Shreveport, Louisiana in 1930 as assistant torsion balance supervisor. From 1932 to 1942 he served various divisions and affiliates of the Gulf Oil Corporation in numerous capacities on torsion balance, pendulum, gravimeter, and seismograph field crews on domestic and foreign assignments.

He entered the U. S. Navy in 1942, served three years aboard aircraft carriers in the Pacific Ocean Area, during which time he attained the rank of Lieutenant Commander, and was transferred

to inactive duty in January 1946, at which time he rejoined the Gulf organization. Shortly thereafter he was assigned his present position as chief geophysicist for Gulf Refining Company at Shreveport. In 1950 he received the B.S. degree in geology from Centenary College of Louisiana.

Mr. Bryan has been a member of the Society of Exploration Geophysicists since 1939. He is also a member of The American Association of Petroleum Geologists, American Geophysical Union, Ark-La-Tex Geophysical Society, Shreveport Geological Society, and Sigma Gamma Epsilon, honorary geological fraternity. He has served successively as Secretary-Treasurer and President of the Ark-La-Tex Geophysical Society.

JAMES L. MORRIS was graduated from West Virginia University in 1936 with an A.B. degree in Geology and received the degree of Geological Engineer (Geophysical Option) in 1938 from the Colorado School of Mines. He was employed upon graduation by The Pure Oil Co., beginning as a magnetometer operator. Subsequent to further geological and geophysical experience in various divisions of the company he served as district geologist, then as a geophysical supervisor of seismic and gravity operations. In 1948 he was promoted to division geologist of the Texas producing division of The Pure Oil Company and since 1949 has served as exploration manager in that division.

He is a member of the American Association of Petroleum Geologists, Ft. Worth Geological Society (Vice President in 1944), the Society of Exploration Geophysicists and the Ft. Worth Geophysical Society (District Representative 1949–50 and Past President).

SOCIETY OF EXPLORATION GEOPHYSICISTS, HOUSTON SECTION SECOND AWARD OF HONORARY MEMBERSHIP

CITATION

T. I. HARKINS

The Award Committee of the Houston Section, S.E.G. has asked me to give a resume of E. E. Rosaire's activities in the geophysical field and it was decided that it would be worth while mentioning some of his background before entering the field of geophysics as well as those subsequent to it.

It gives me a great deal of pleasure to be able to do this because I, along with numerous others, have the fee ling that Gene did more to help geophysics to attain its present position than any other one individual.

He received his M.S. degree from Chicago in 1921 and his Ph.D. from the same school in 1926. He was in the Development Branch of the Western Electric from 1922 to 1925 and was employed by the Geophysical Research Corporation and sent to Texas in the spring of 1925 to organize two field parties contracted to the Gulf Production Company (now Gulf Oil Corporation). While he was in charge of the second party the Moss Bluff salt dome was found. This was the first American seismograph crew to find and locate a salt dome. Three weeks later this same crew discovered the Port Barre dome in south Louisiana.

Rosaire was transferred to Oklahoma in 1926 to direct Amerada Petroleum Corporation's reflection work. He came back to the Gulf Coast in 1927 where he had charge of all Geophysical Research Corporation's contract work. He remained with G.R.C. until 1932 and during this time reflection dip shooting was developed in the Gulf Coast. In 1932 he helped to organize the Independent Exploration Company which consisted of a number of ex-G.R.C. men. As head of the Independent Exploration Company he originated and developed the idea of using traverse misclosures to detail faults associated with Gulf Coast structures. He resigned as president of the Independent Exploration Company in 1937 to enter the soil analysis and electrical prospecting field. He originated the idea of analyzing well cuttings to predict the nearness of the bit to the oil sands. He presently lives in Dallas and is a partner of the Geochemical Surveys, Inc.

In 1930 the Society of Petroleum Geophysicists was organized in Houston, Texas, and Gene was one of the charter members and helped to organize this association. The late Donald Barton was

elected president, E. E. Rosaire, vice-president, and John Weinzerl, secretary-treasurer. Gene was elected president in 1934. He helped to organize and write the charters and by-laws of the Houston section of the Society. He has always been very active and interested in all phases of the Society's work.

Gene was an Air Force Lieutenant during the First World War. He was elected to the Order of Quiet Birdmen in 1927. This is an association of ex-military fliers who have achieved some special distinction in the war other than in the line of duty. His particular achievement was that of being the

DOCTOR ESME EUGENE ROSAIRE

Recipient, Second Award of Honorary Membership

Houston Section

May 25, 1951

leading German ace in the American army. He wrecked five U. S. planes in one day, which was his biggest day.

He originated four handed chess and has written a book on rules and how to play the game. He did considerable work on tax research in the City of Houston and helped to reorganize the Tax Research Association.

The above facts are only the highlights of Gene's career and there are numerous others that should be mentioned but it was the purpose of this citation to be brief and touch only on his outstanding achievements. Again I want to say that this has been a pleasure to me, and I want to thank the Committee for favoring me with the opportunity of preparing this résumé.

EASTERN REGIONAL MEETING

The Executive Committee of the Society of Exploration Geophysicists has authorized an Eastern Regional Meeting which will be held in Pittsburgh, Pennsylvania on October 25, 1951.

The one-day program is planned to be of general interest to geophysicists and geologists and will not be limited to local subjects. The geophysicists will be guests of the Pittsburgh Geological Society for an evening meeting at which Dr. W. C. Krumbein will speak.

The meetings will be held in the Mellon Institute Auditorium and registration will be in the ad-

jacent foyer. Blocks of rooms for this meeting have been reserved by two hotels; the Webster Hall, across the street from Mellon Institute, will be Headquarters Hotel and has a few single rooms from $5.50 to $7.00 and double rooms from $8.00 to $12.00. The Schenley Hotel, one block from Mellon Institute, has double rooms from $8.00 to $12.00. When requesting reservations be sure to notify the hotel that you will attend the SEG Eastern Regional Meeting.

Everyone registered at the meeting will be invited to tour the Mellon Institute of Industrial Research and the Gulf Research & Development Company laboratories on the following day, Friday, October 26th.

R. B. Ross has been named General Chairman of the meeting and with Dr. Frank Press is arranging the program. Local arrangements are being made by L. F. Melchior assisted by W. B. Robinson and David A. Davis.

ANNUAL PACIFIC COAST MEETING

November 1 and 2, 1951

The Pacific Coast Section, Society of Exploration Geophysicists, will hold its annual fall meeting on November 1 and 2 at the Ambassador Hotel in Los Angeles. The meeting will again be held in conjunction with the annual sessions of the Local AAPG and SEPM groups and coordinated programs will be presented. Flint Agee, of United Geophysical Co., Pasadena, vice president of the southern division of the Pacific Coast Section, will be in charge of program and arrangements for the S.E.G.

More than 200 exploration scientists on the West Coast are members of the Pacific Coast Section. Officers of the society are: John Sloat, Union Oil Co. of California, Bakersfield, vice president, Northern District; Flint Agee, vice president, Southern District; O. K. Fuller, Jr., Humble Oil & Refining Co., Los Angeles, Secretary-Treasurer; John D. Hale, Seaboard Oil Co., Bakersfield, district representative to the S.E.G.; and V. E. Prestine, Western Geophysical Co., Los Angeles, district representative to the S.E.G.

ANNUAL MIDWESTERN REGIONAL MEETING

November 19 and 20, 1951

The Baker Hotel, Dallas, Texas, will be the scene of the annual joint meeting sponsored by the Dallas Geophysical Society, Fort Worth Geophysical Society, Permian Basin Geophysical Society, Ark-La-Tex Geophysical Society, and Geophysical Society of Tulsa. The Tulsa Section will be in charge of general arrangements through a committee composed of E. M. McNatt, J. P. Garner, K. M. Lawrence, W. H. Courtier, Frank Searcy, and Karl Dyk, Chairman. Most of the papers presented during the two-day meeting will concern geophysical problems encountered in the midwestern oil producing region of the United States, including a featured address by Dr. B. B. Weatherby. More than one thousand are expected to attend. Detailed announcements will be mailed to all members of the society well in advance of the meeting, along with hotel reservation forms. Those who await receipt of the official announcement will be assured of obtaining better accommodations, since the hotels have reserved space for delegates who apply on the official form.

TWENTY-SECOND ANNUAL MEETING

March 23–27, 1952

The next Annual Meeting of the Society of Exploration Geophysicists will be held March 23–27, 1952 in the Biltmore Hotel, Los Angeles, California. The society will again meet jointly with The American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists. Curtis H. Johnson, Vice President, is general chairman of program and arrangements for the S.E.G., and Furman A. Grimm is vice chairman in charge of local arrangements.

The official announcement of this meeting will be mailed in the near future to all members of the society, along with the official hotel reservation form. Members are urged to await receipt of the

official announcement before requesting accommodations, inasmuch as the hotels will reserve their more suitable rooms for those whose requests are made on the official form.

ANNUAL GULF COAST MEETING

May 29 and 30, 1952

Tentative dates have been set by the Houston Section for a two-day meeting on May 29 and 30, 1952 at the Rice Hotel in Houston, Texas. Although the actual plans of the meeting have not been formulated, this announcement is made for the benefit of those companies and individuals who wish to schedule the attendance of their personnel in advance. Development of program plans and arrangements will be announced in future issues of *Geophysics*, and an official notice will be mailed to all members of the society well in advance of the meeting.

Eugene W. Frowe, of Robert H. Ray Company, vice president of the Houston Section, is in charge of program and arrangements.

DEMAND INCREASING FOR OUT OF PRINT ISSUES

Recent expansion of curricula to include courses in exploration geophysics has created a further demand for complete files of *Geophysics* in universities throughout the world. Almost daily the business office must report to new subscribers that certain back numbers of the Journal are not available. Members of the society and subscribers to *Geophysics* are urged to report to the business office any of the following numbers for which they have no further use, in the interest of making available this essential literature on exploration geophysics.

1938	Volume III	Numbers 1, 3 and 4
1940	Volume V	Number 1
1941	Volume VI	Numbers 1 and 4
1942	Volume VII	Number 1
1943	Volume VIII	Numbers 1, 2, 3 and 4
1944	Volume IX	Numbers 1, 2, 3 and 4
1945	Volume X	Numbers 1 and 2
1947	Volume XII	Number 1

PERSONAL ITEMS

K. A. ROBERTSON, formerly manager of the Calgary office of United Geophysical Company, is now president of Precision Exploration Company with offices at 409 Palace Building, Tulsa, Oklahoma.

JOHN W. DALY, West Texas supervisor of General Geophysical Company, spoke at a meeting of the Canadian Society of Exploration Geophysicists August 24 on the subject, "How Seismograph Interpretation is Related to Changes in the Sedimentary Section." The meeting was held in the Palister Hotel, Calgary.

LORENZ SHOCK announces the opening of the Midland Geophysical Company with offices at 233 Capitol Building, Midland, Texas.

JACQUES SCHOEFFLER, field geologist with Societe Cherifienne des Petroles, Rabat, Morocco, is in the United States under the sponsorship of the Economic Cooperation Administration. While here he will obtain training in geophysics at the University of Texas and Colorado School of Mines, and at the same time he is visiting various contracting and producing companies for what the ECA calls "in-plant" study of oil exploration in the United States. Upon returning to Rabat Mr. Schoeffler will become chief geophysicist of his company. He has visited the business office of the society and has applied for membership.

ROBERT DYK, formerly senior geophysicist for General Petroleum Corporation, has joined Geophysical Service Inc., as manager of the Rocky Mountain division with headquarters in Denver, Colorado. Prior to this change he was located in Bakersfield, California, and was president of the Pacific Coast Section of S.E.G.

R. G. SOHLBERG, formerly in charge of the geophysical division of Richmond Exploration Co. (Standard Oil Co. of California) at Maracaibo, Venezuela, has resigned his connection with that organization and has accepted the position of manager for United Geophysical Company of Canada, with offices at Calgary, Alberta.

H. K. HERR, formerly with Kerr-McGee Oil Industries, is now seismic party chief for the Rayflex Exploration Company at Miles City, Montana.

W. J. BUSTEED, former Secretary-Treasurer of the Colorado School of Mines Society of Student Geophysicists, is now with Geophysical Service Inc., at 6000 Lemmon Avenue, Dallas 9, Texas.

F. REX WALLING, JR. has resigned from Stanolind Oil & Gas Co. and is now connected with the Grant Oil Tool Co., and MacClatchie Manufacturing Co., at Odessa, Texas.

STANFORD L. MYERS has been appointed equipment and safety supervisor of Southern Geophysical Company with offices in Fort Worth and Midland, Texas.

ROBERT L. GEYER has resigned from the faculty of the School of Geology, Louisiana State University, to accept the position of geophysicist with the Stanolind Oil & Gas Company. His address is 1815 North Cheyenne, Tulsa 6, Oklahoma.

J. S. WELBOAN, JR. has been promoted to Assistant to Division Manager of the geophysical division, producing department of The Texas Company. Employed shortly after graduation from the University of Oklahoma in 1935, Mr. Welboan has served the Texas Company successively as computer, party chief, and supervisor.

A. E. MCKAY, formerly assistant chief geophysicist for The Atlantic Refining Company, and from June 1950 to July 1951, executive vice president of Southern Geophysical Company, announces the organization of Continental Geophysical Company with offices at 6100 Camp Bowie Blvd., Fort Worth, Texas.

E. F. K. ZARUDSKI has resigned from Seismograph Service Ltd., London, to accept the position of party chief with Century Geophysical Corporation in Canada, at 615 8th Avenue West, Calgary, Alberta.

J. L. KEZELER has been named executive vice president in charge of field operations of Standard Seismograph Company, Oklahoma City, it was announced by the company president, C. C. CODY. Kezeler recently resigned from the position of chief geophysical engineer with Century Geophysical Corporation to accept the new position.

SIDON HARRIS, president of Southern Geophysical Company, announces publication of the first issue of "Southern Record," company house organ to promote good will among Southern employees and to keep widely separated crews informed on activities of fellow workers.

C. T. RANKIN, party chief with Amerada Petroleum Corp., has been transferred to Glasgow, Montana.

JOE L. MOORE has resigned from Honolulu Oil Corporation to establish offices as consultant in Midland, Texas.

CHARLES C. BATES, consultant with A. H. Glenn & Associates, has moved from Washington,

D. C., to College Station, Texas, to complete work toward a Ph.D. degree in geological oceanography at A. & M. College of Texas.

ROBERT K. YOUNG, party chief for Continental Oil Co., is now located in Duncan, Oklahoma.

DONALD M. DAVIS has opened consulting geological offices at 822½ Moraga Drive, West Bel-Air, Los Angeles 49, California. Mr. Davis was formerly with the Union Oil Company of California and Richfield Oil Corporation. Prior to this he was with United Geophysical Company in the capacity of party chief. He will specialize in problems relating to the Sacramento Valley of California.

PHIL P. GABY has resigned from the California Standard Company, and is now engaged as a partner in Delta Exploration Company and as manager of the Canadian branch office located at 536 8th Avenue West, Calgary, Alberta.

W. DAY WALDREP has taken the position of senior map draftsman in the exploration department of Sunray Oil Corporation at 1509 First National Building, Tulsa, Okla.

R. H. DANA has been promoted from vice president to executive vice president of Southern Geophysical Company. W. D. BAIRD has moved from treasurer and supervisor to vice president, and R. E. DAVIS from supervisor to assistant vice president of the company.

THE NATIONAL RESEARCH COUNCIL announces that its Committee on Geophysics, Advisory to the Office of Naval Research will meet 7 November, 1951. The Committee will advise the Office of Naval Research on proposals received by it in the field of geophysics. Those wishing support in basic research in this field should submit five copies of their proposal and a letter of endorsement signed by the President or other duly authorized financial officer of their institution. These should be sent in each case to the Commanding Officer of the ONR area branch office for that district. In addition, at least one advance copy should be sent to the Geophysics Branch, Office of Naval Research, Department of the Navy, Washington 25, D. C. To insure consideration at the forthcoming meeting of the Committee, such proposals should be received by ONR in Washington not later than 1 October, 1951.

THE AIR FORCE ANNOUNCES that men in civil life, either veterans or non-veterans with a degree in civil engineering, geology, or photogrammetric engineering can now enter the Air Force directly as officers, with a topographic engineer commission. This announcement was made at First Air Force headquarters at Mitchel Air Force Base, New York, by Major Charles D. Morat, Jr., Director of Military Personnel Procurement.

Major Morat said that experience to qualify a man for this commission must be in these fields: engineering, surveying, cartography, topographic drafting, geodetic surveying, or other related fields. Experience in lithographic and reproduction work is also desirable. More specifically, an applicant must have technical knowledge of survey work, such as determining exact locations and measurements of points, elevation lines, areas and contours on the earth's surface; or, should be experienced in photogrammetric and cartographic draftsmanship; or, photographic laboratory methods, photo-transferring and lithographic processes, or the operation and maintenance of lithographic equipment.

Appointments will be made in grades from first lieutenant through lieutenant colonel, depending on age. Inquiries should be addressed to the Department of Military Personnel Procurement, Headquarters First Air Force, Mitchel Air Force Base, New York, or phone Garden City 3-4000, extension 3202.

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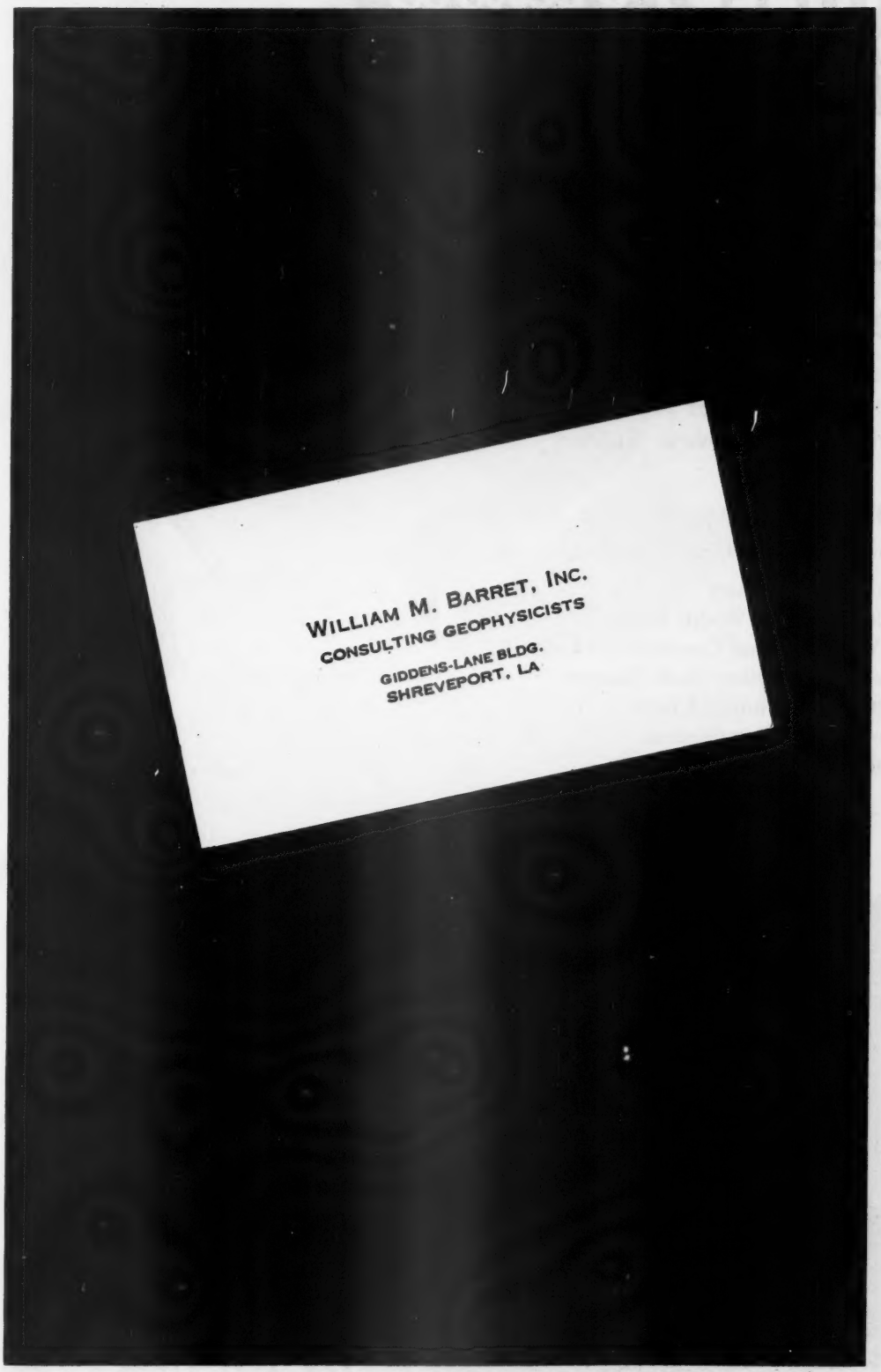
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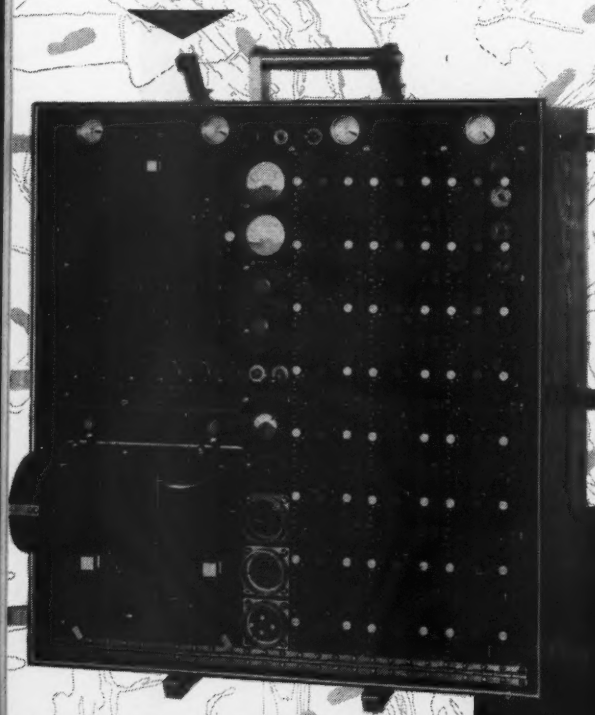

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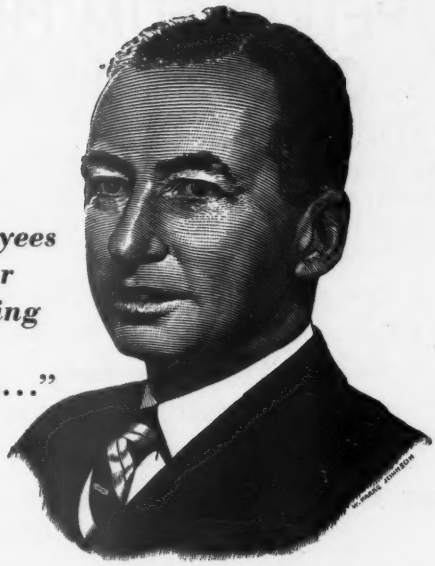

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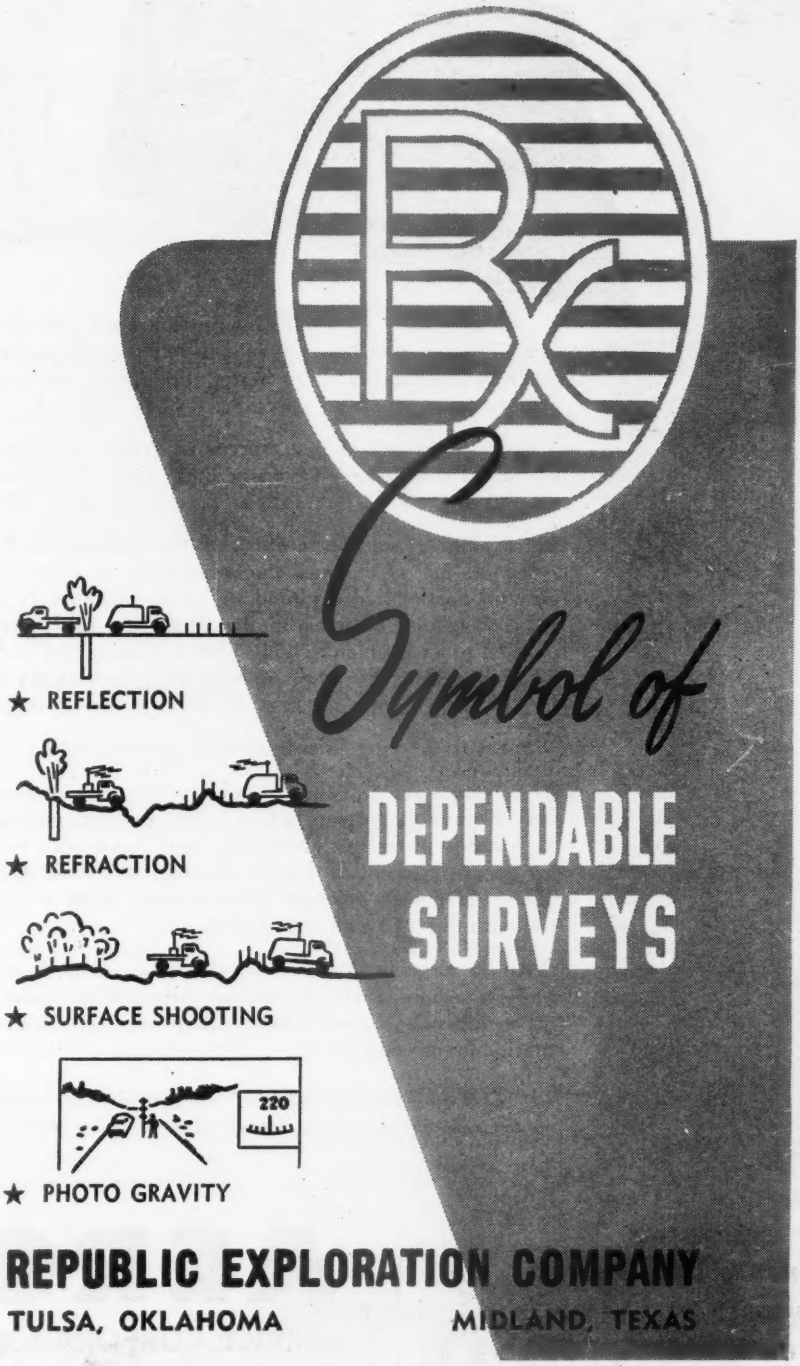
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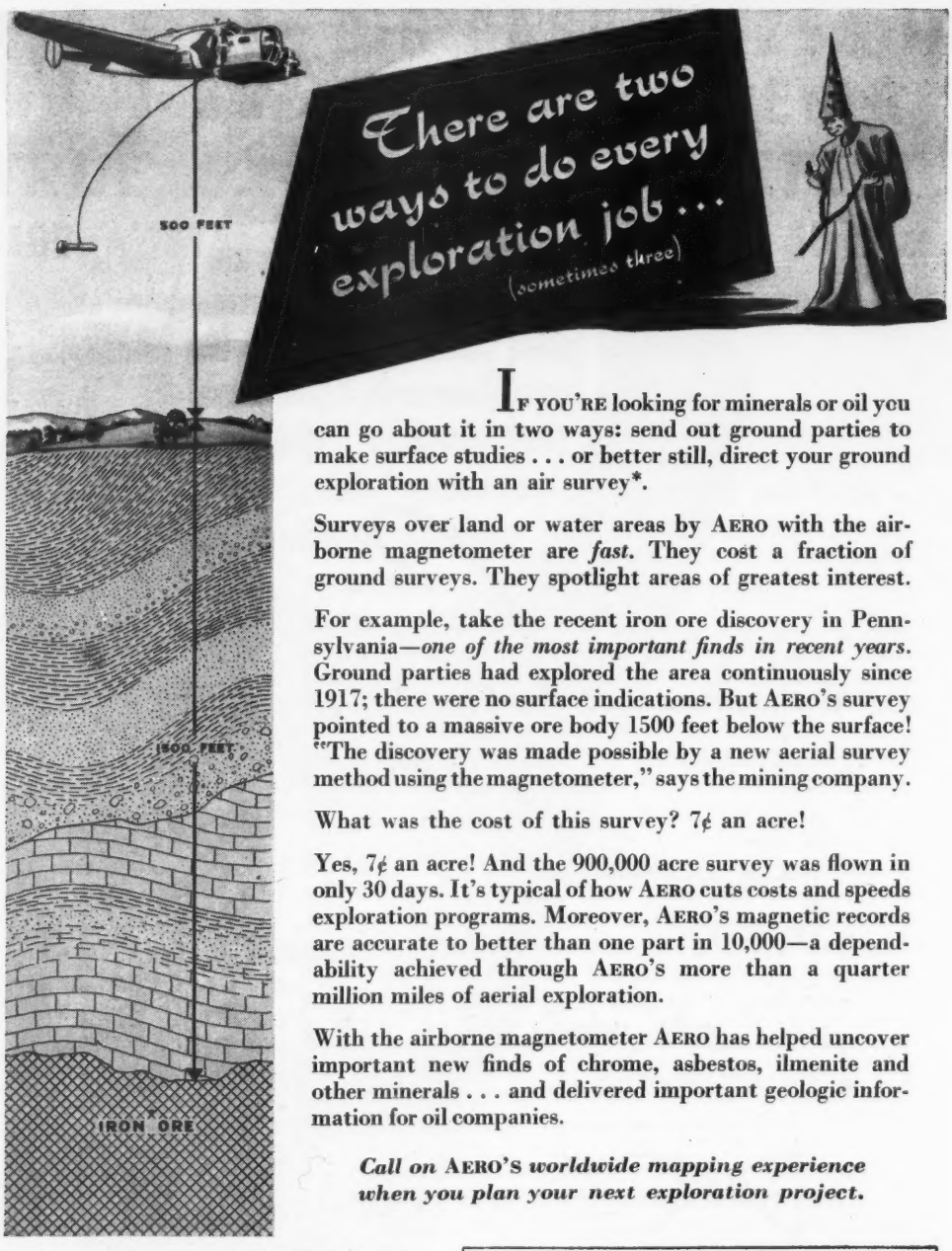

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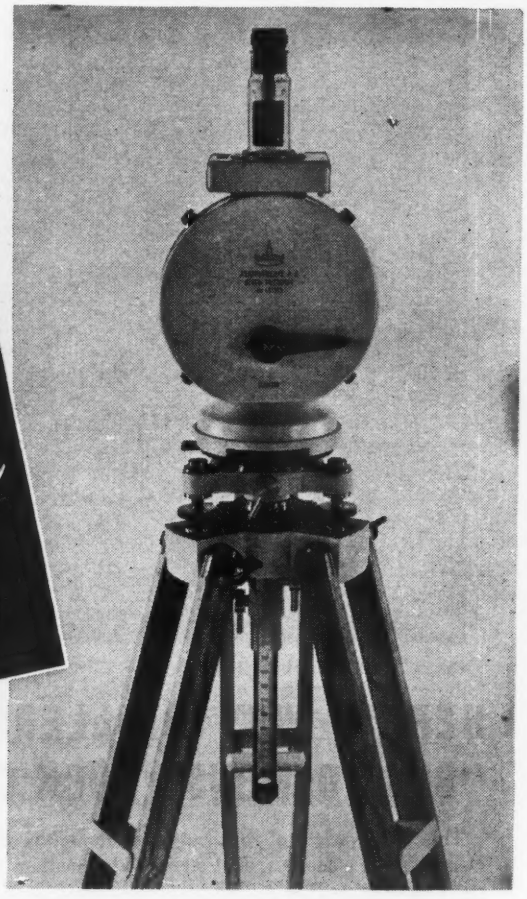

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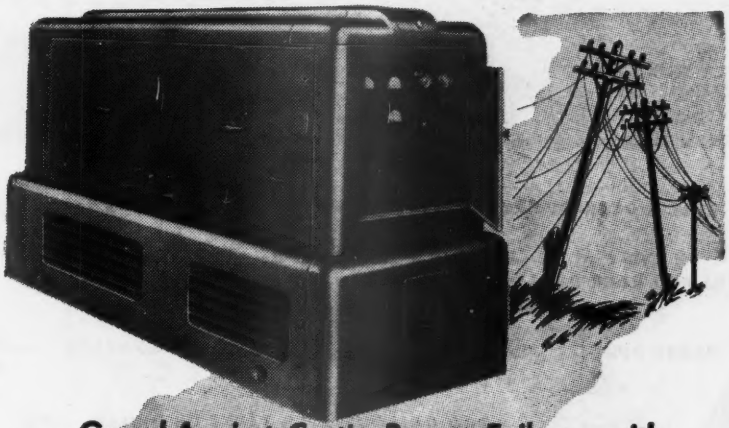

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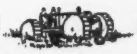

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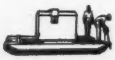

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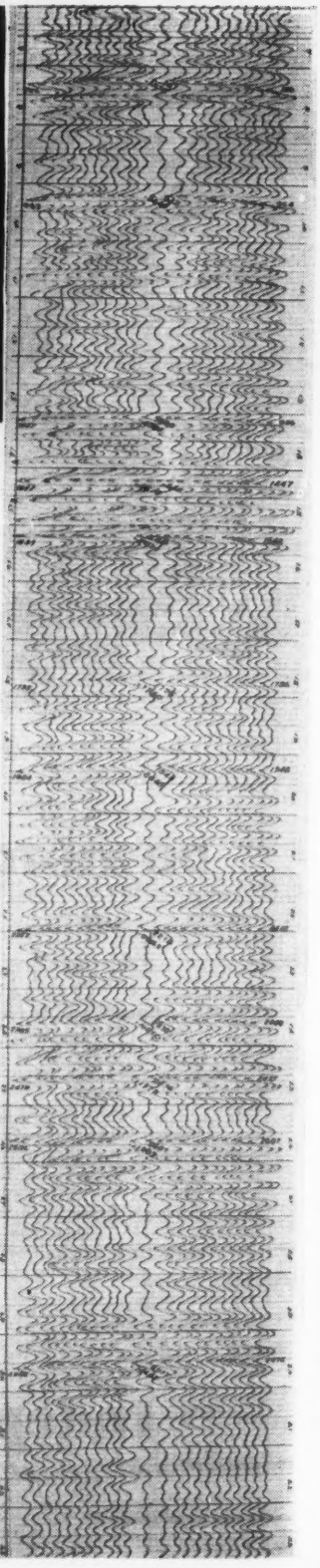

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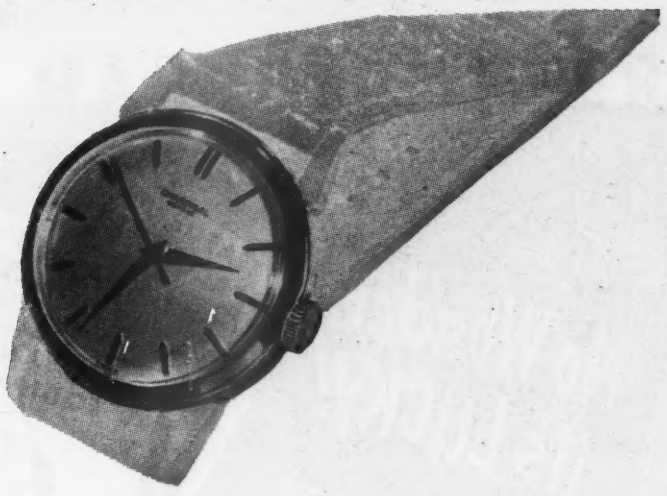

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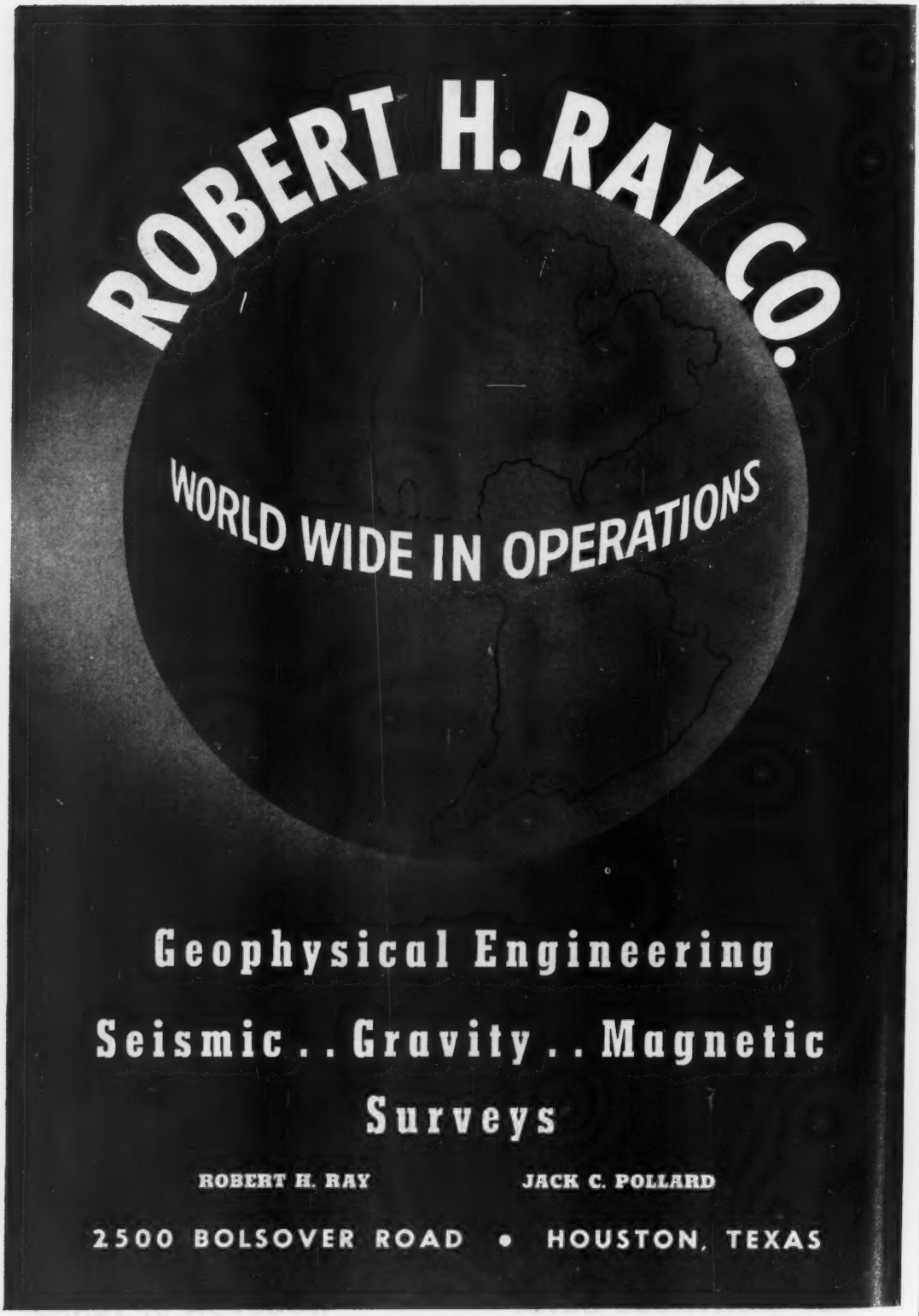

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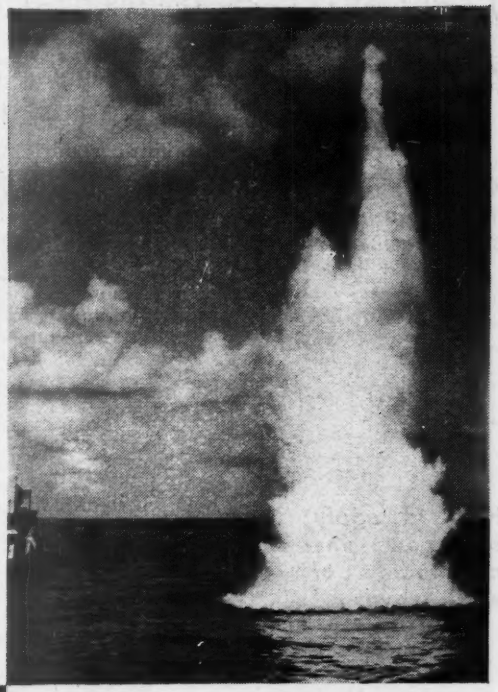

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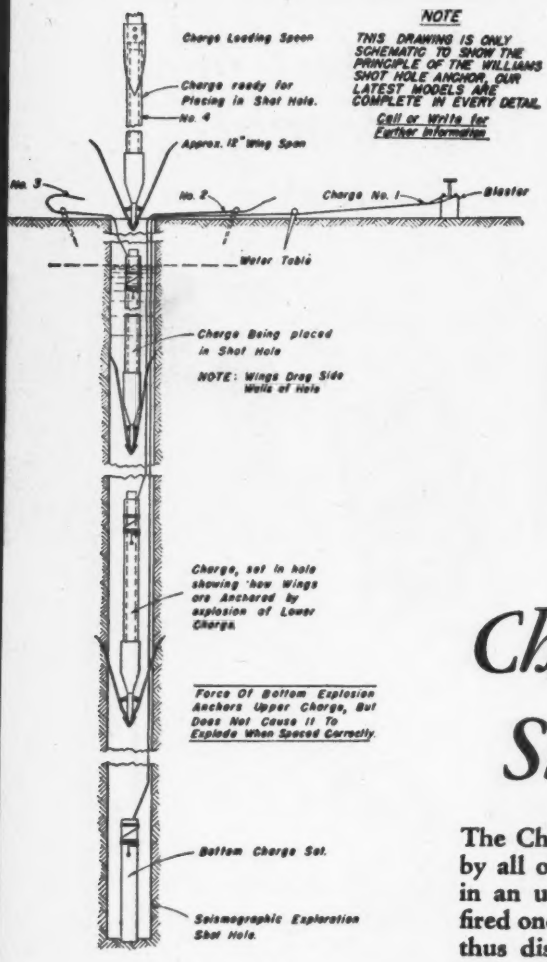
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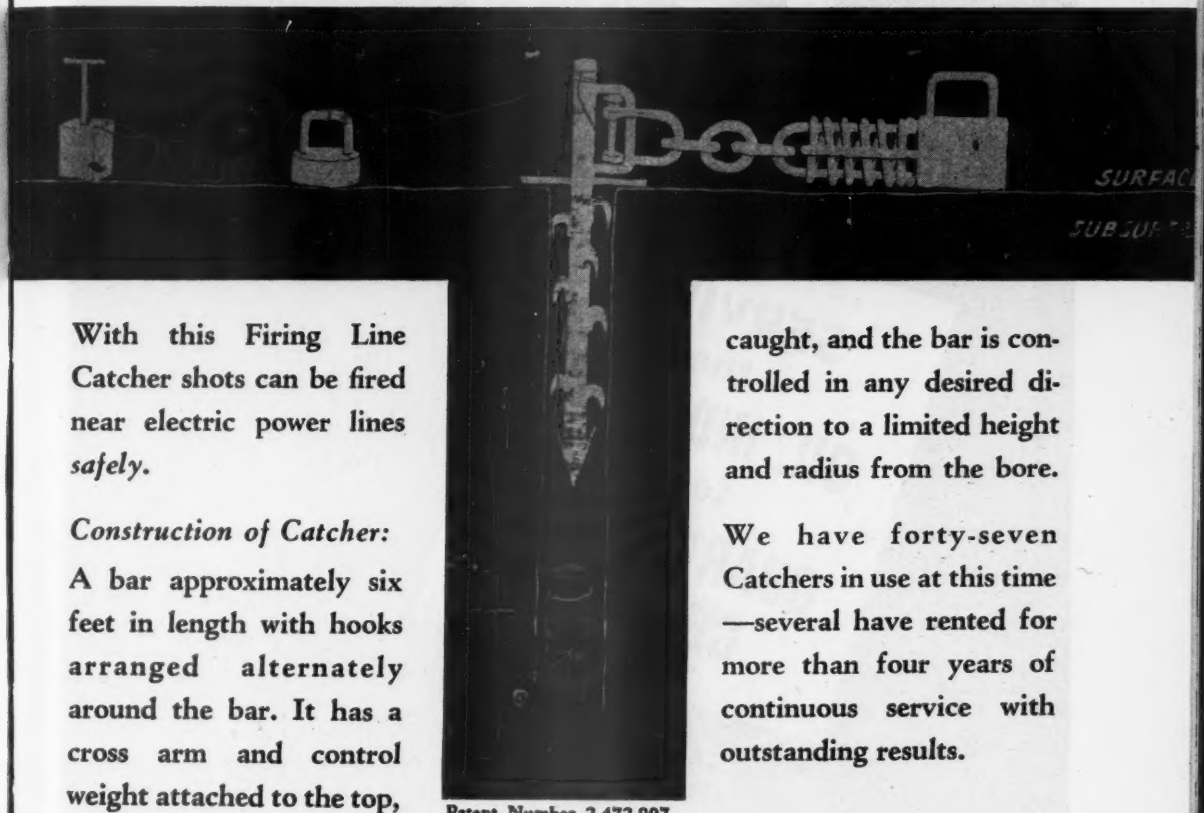

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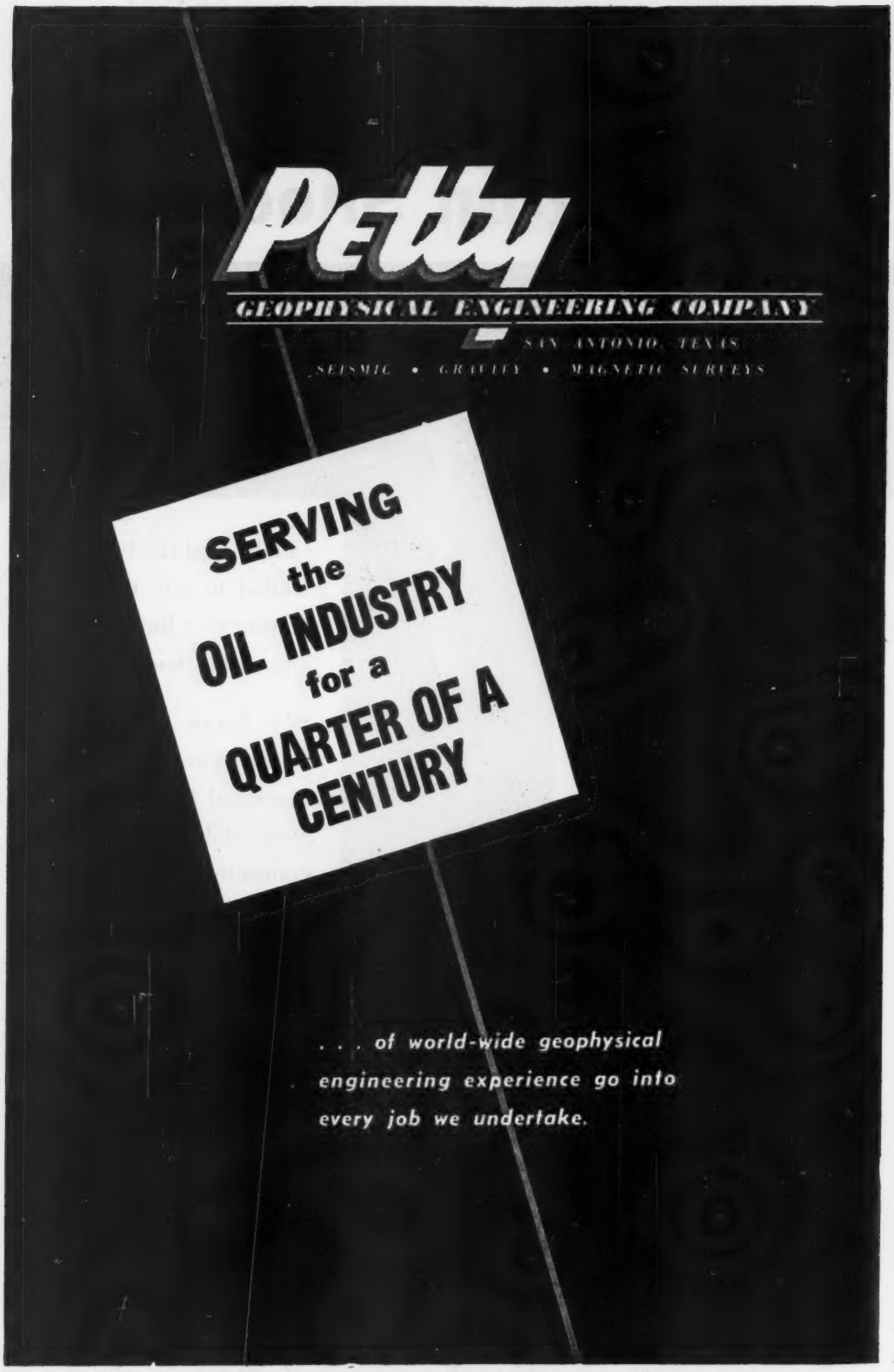
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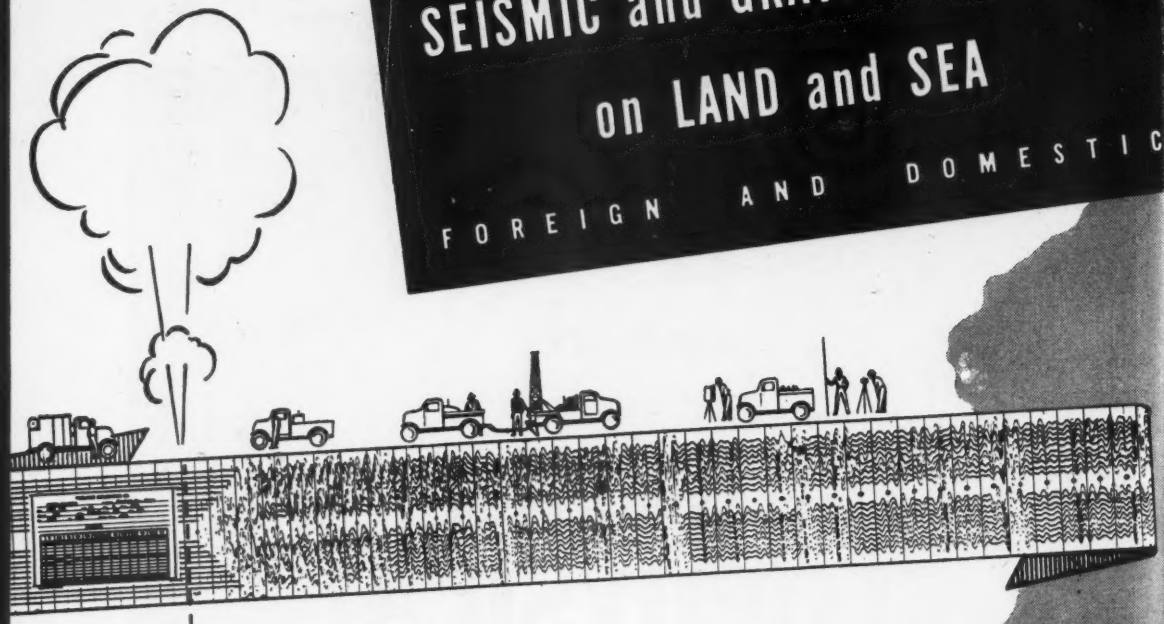

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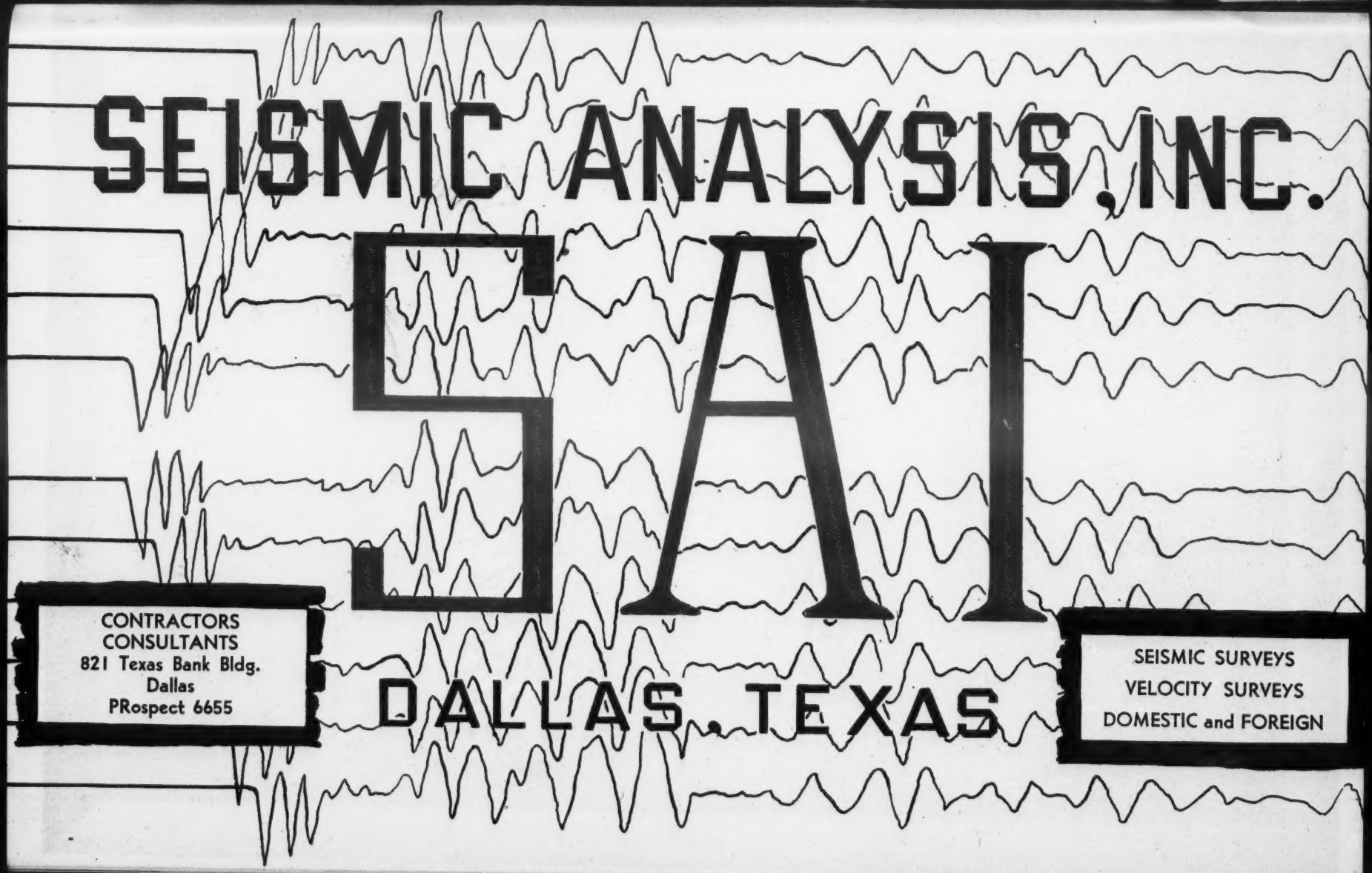
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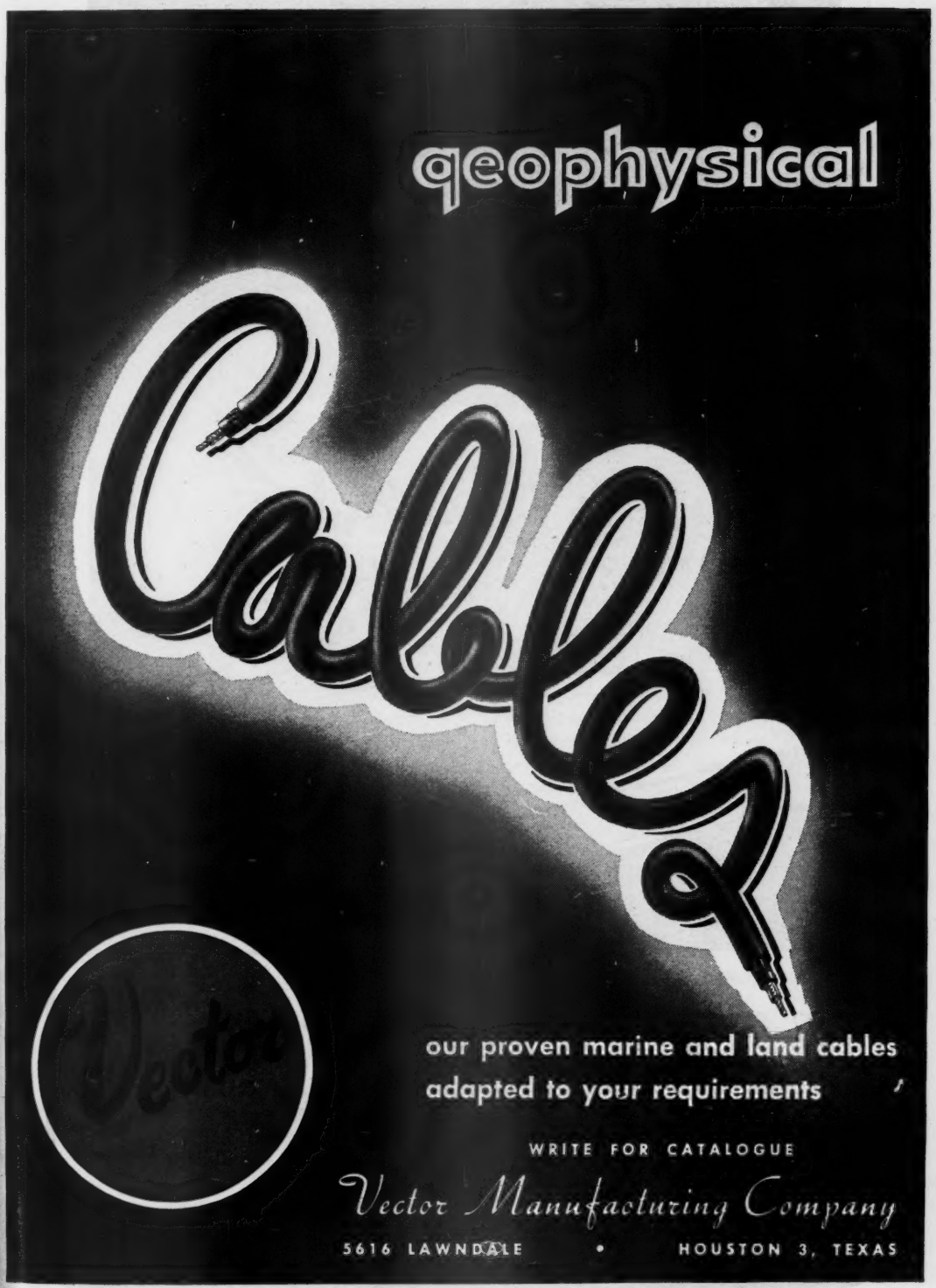
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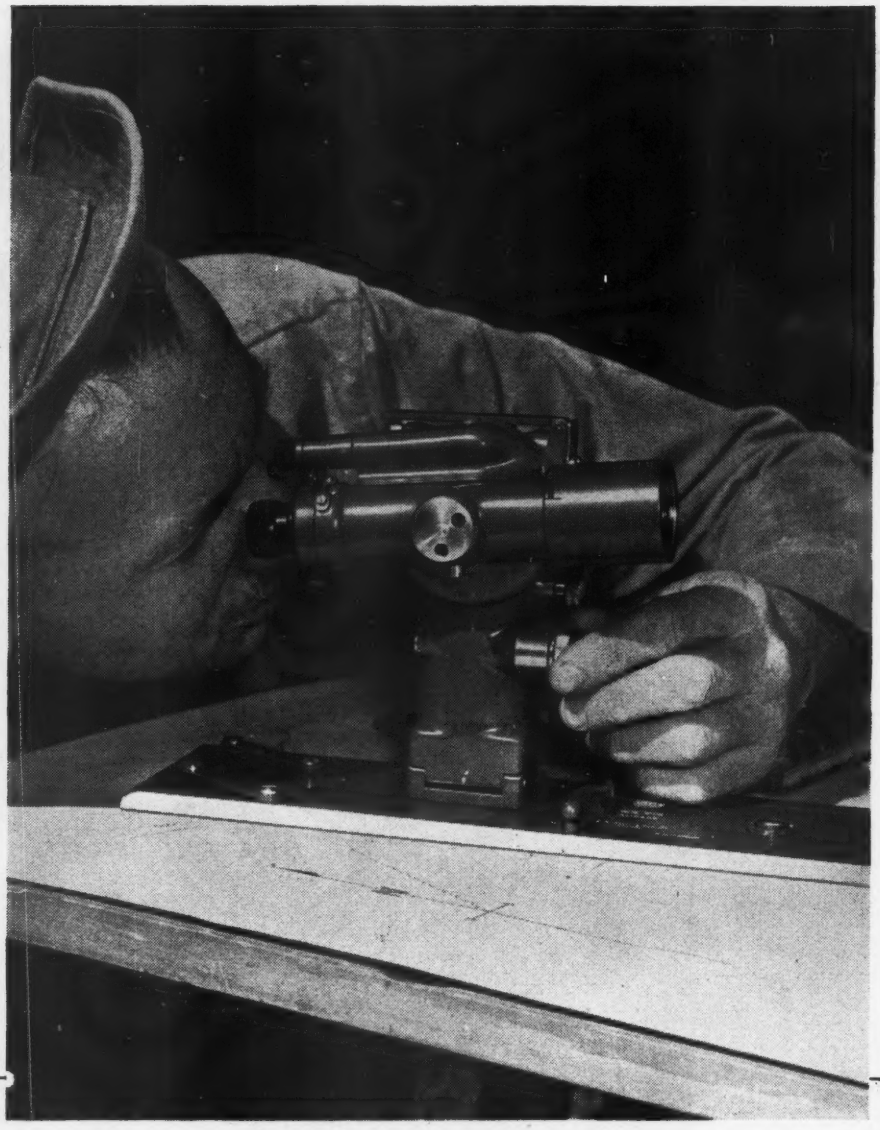

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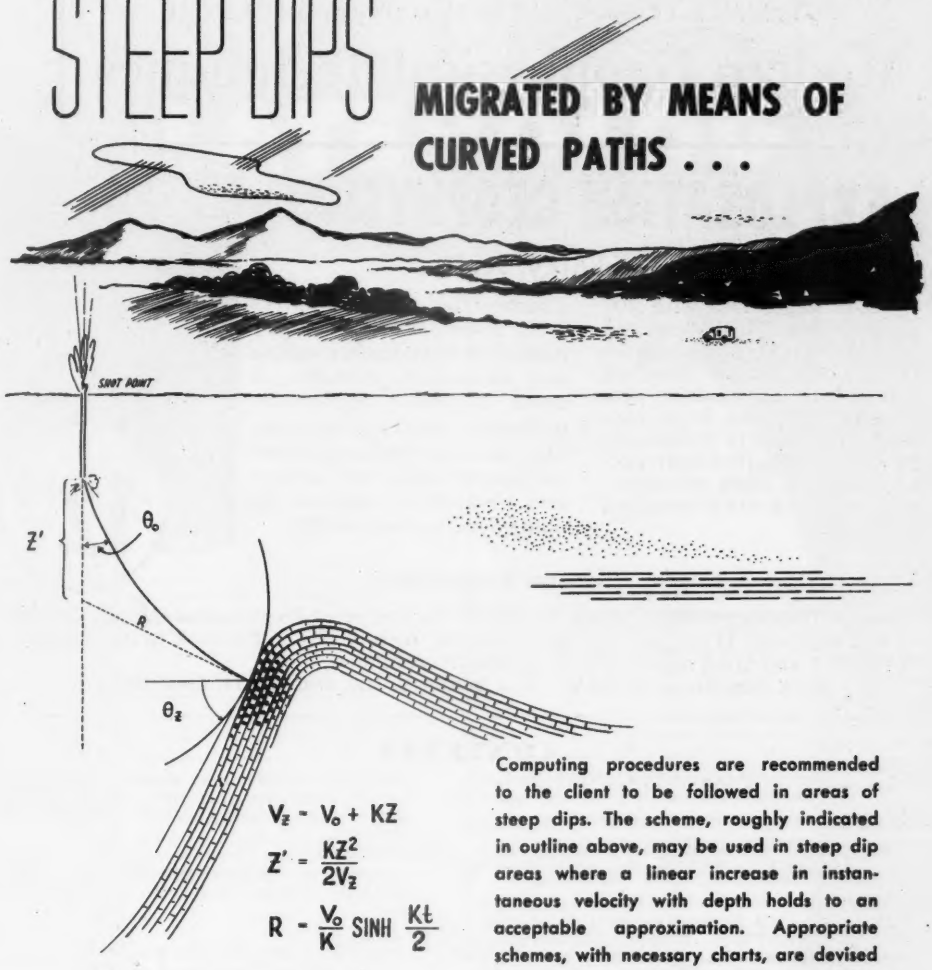

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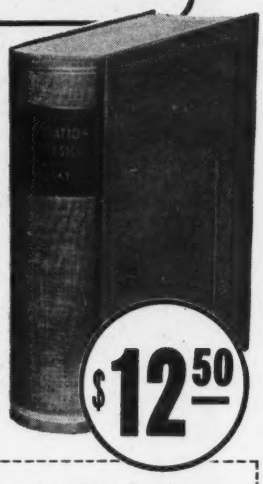

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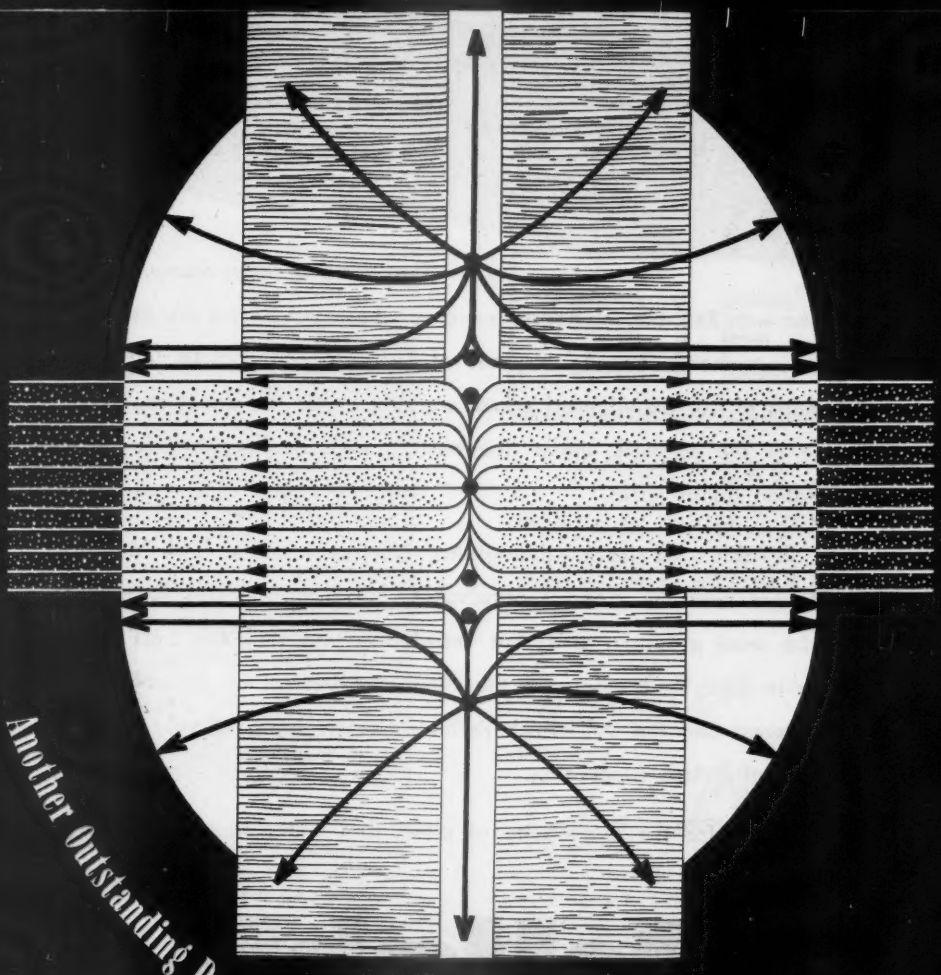

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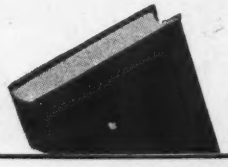

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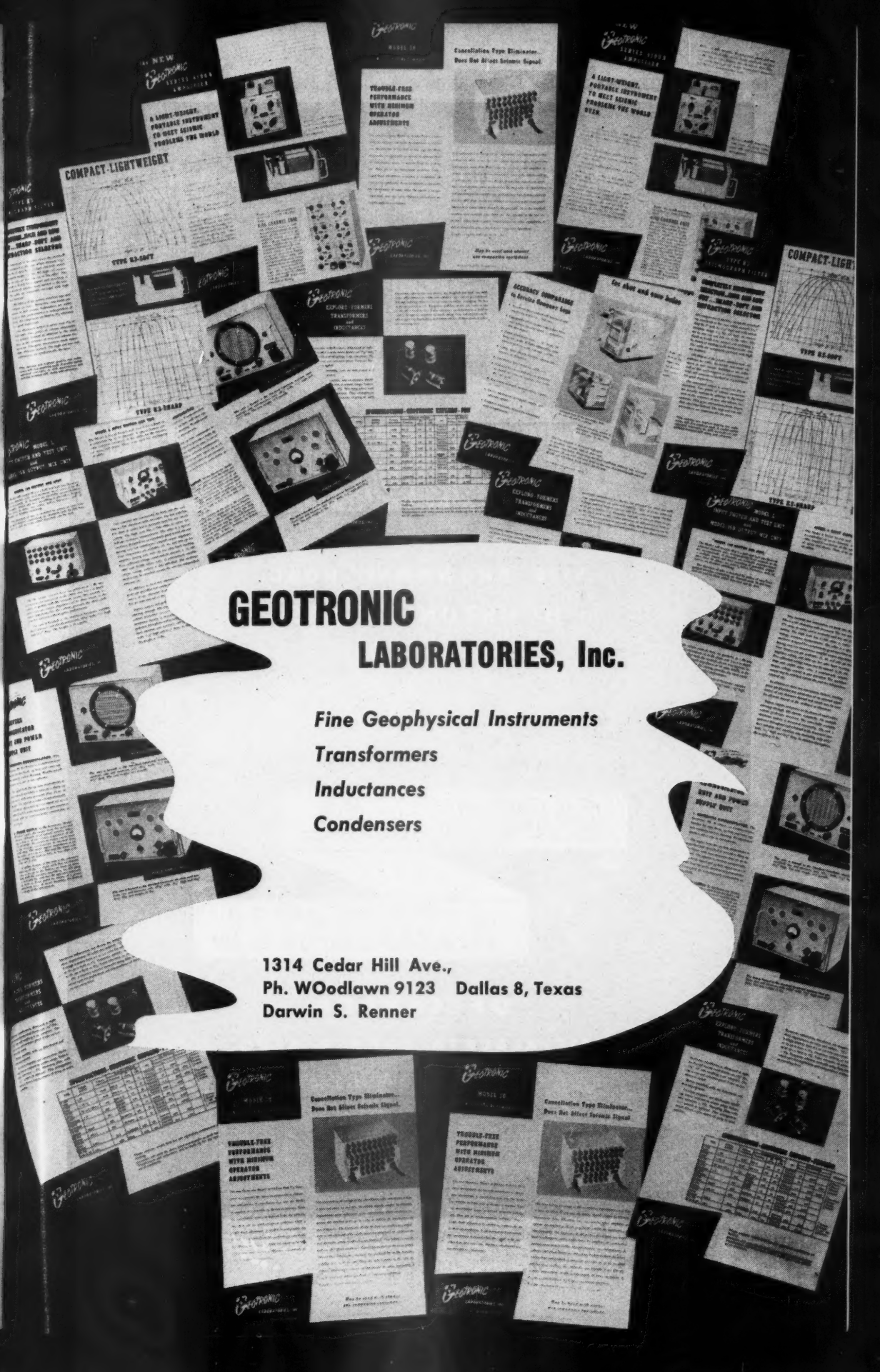
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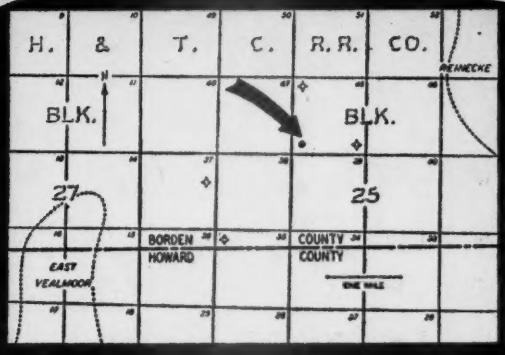

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